499

A Study of Ocean Fronts off Cape San Lucas, Lower California

By Raymond C. Griffiths

SPECIAL SCIENTIFIC REPORT–FISHERIES No. 499

UNITED STATES DEPARTMENT OF THE INTERIOR
FISH AND WILDLIFE SERVICE

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Washington, D.C.

February 1965

CONTENTS

FIGURES

Page

TABLES

A Study of Oceanic Fronts off Cape San Lucas, Lower California [1]

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ABSTRACT

The general concept of a front is discussed, with some emphasis on the problem of strict definition and on the probable effects of a front on the biota. A note is made of the lack of precise studies, particularly biological studies.

Some of the difficulties in obtaining observations at five fronts off Cape San Lucas are mentioned.

Data from two cruises in April and May 1960 are used to depict the main oceanographic features of the area at large.

The most easily studied, sharpest, and most stable front was found off Cape San Lucas on a cruise in April 1961. Here warm, saline Gulf of California water moved slowly, inshore, while cool, less saline California Current water moved slowly eastward offshore, the front being maintained between them. Profiles of all the main oceanographic variables across the best studied front were drawn from data of two triplets of hydrocasts, a day apart, across the front. The vertical temperature and salinity distributions showed the interface between the two water masses to be Z-shaped.

Animal and plant plankton and nekton were measured in relation to this front, but the evidence for accumulation of biota at the front is not conclusive.

Four other fronts were studied, though not as thoroughly; the data from them are used to illustrate certain difficulties in studying fronts.

INTRODUCTION

Since June 1957, the Scripps Tuna Oceanography Research (STOR) Program of the Scripps Institution of Oceanography (SIO) has been concerned with "An oceanographic investigation of causes, mechanisms, and predictability of changes in availability of tuna in the eastern tropical Pacific." The work is supported by the U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries. This paper shows results of oceanographic studies related to this research. Yellowfin tuna, in particular, and possibly skipjack, migrate in the spring or early summer across the entrance of the Gulf of California from the waters off western Mexico to waters off western Lower California (Schaefer, Chatwin, and Broadhead, 1961). The most prominent oceanographic features of the Gulf's entrance at that time are oceanic fronts. This raised the question of whether the occurrence of these fronts are related to the movements of the tuna,[2] either directly and physically or indirectly due to the effects of the fronts on the biotic regime in the area.

To answer this question we first need to know something of the structure of, and distribution of properties in and about, these fronts, including the kinds of water forming them. The main purpose of this paper is to present the results of STOR's preliminary investigations of these phenomena.

STOR cruise TO-60-1 (30 April to 26 May 1960), with M. V. Hugh M. Smith, investigated:

[1] The study is a contribution from the Scripps Institute of Oceanography, University of California, San Diego.

Note.--This work was financed by the Bureau of Commercial Fisheries under Contract Nos. 14-19-008-9354, 14-17-307-1, 14-17-0007-28 and 14-17-0007-70, with funds made available under the Act of July 1, 1954 (68 Stat. 376), commonly known as the Saltonstall-Kennedy Act.

[2] Henceforth the word "tuna" will be used when referring generally to both species; the common names, yellowfin and skipjack, will be used when referring specifically to one or the other.

(1) the physical, chemical, and biological properties of the entrance to the Gulf of California at the time of year when tuna are normally abundant there (Alverson, 1960; Griffiths, 1960); and (2) any oceanic fronts found there, California Cooperative Oceanic Fisheries Investigation (CalCOFI) cruise 6004 (M. V. Black Douglas) which ended at Cape San Lucas, Lower California, on 30 April 1960, provides supplementary data nearly contemporaneous with those of TO-60-1, in the area immediately north of Cape San Lucas, off western California. Further supplementary data were obtained from several CalCOFI and other cruises to the area around Cape San Lucas (or nearby Cape Falso). The references of the data reports of these cruises are given in the bibliography.

The fronts discovered on TO-60-1 in May 1960 were numbered 1, 2, 3, and 4; they formed a valuable basis for the more intensive study of one front (no. 5) at the end of STOR cruise TO-61-1 in April 1961. The results of this latter study form the body of this paper.

The term "front" apparently is a meteorological term that has been widely adopted by oceanographers, but it has no precise definition in oceanography. Cromwell and Reid (1956) say, "A front will mean a band along the sea surface across which density changes abruptly." This definition does not specify the cause of the density change, which may be due to a change in either salinity or temperature, or both. Accordingly, this leads to the use of such terms as "temperature fronts" or "salinity fronts."

Uda (1959) says that a front (siome) is a boundary between two different kinds of water: "Then the boundaries of the water mass are in a region where the gradients of the property are maximum (i.e., the Polar Front, etc.)."

La Fond (1961a) states: "The leading edge of a border separating unlike water masses is called a front. Fronts can occur not only between water masses of different salinity but also between those differing in other properties, such as temperature."

Undoubtedly the term "water mass" is used loosely in these definitions and does not imply the specific definition given by Sverdrup, Johnson, and Fleming (1942). Fronts often are found, for example, between upwelled and nonupwelled water, though both kinds are from one water mass in the sense of Sverdrup et al.

It is difficult to achieve a precise numerical definition of a front. Uda (1959) specifies a front, in terms of a temperature gradient, as ranging from 0.5° C./10 miles to 5.0° C./10 miles, which illustrates the lack of precision in defining a front.

I propose to use the term "frontal system" for the whole boundary between two kinds of water, reserving the word "front" for those small parts of the system that actually are investigated. Convergent and divergent fronts are terms occasionally encountered and are derived from the terms convergence and divergence as commonly used in oceanography.

Uda (1959) and Griffiths (1963) reviewed the research on the major frontal systems of the world oceans.

It is widely believed that convergent fronts mechanically aggregate plankton. Uda (1938) described the accumulation of flotsam at siome (fronts), and Uda and Ishino (1958) indicated that convergent fronts show a line of biological demarcation owing to aggregation of biota. Hela and Laevastu (1962), without quoting specific references, illustrate plankton accumulated in a front. La Fond's (1961a) definition, stated above, continues: "These fronts raise water of higher nutrient content to the surface. In addition, the fronts tend to concentrate floating fish food in adjacent areas." This raises the question of whether a front manifests a higher standing crop of plankton than does water on either side, either by aggregating the biota or by causing conditions specially favorable to the growth of a higher standing crop. This, in turn, probably depends on whether the front is convergent, in which case aggregation might be expected, or divergent, in which case nutrient-rich water might be brought to the surface to increase plankton growth. Uda (1959) suggested that the latter occurs at siome, though those fronts he discusses apparently are convergent. Evidently, there is a conflict of possibilities. Siomina (1958) stated that phytoplankton "blooms" are a feature of the area of mixing between the Kuroshio and Oyashio, but he does not say whether these "blooms" are a result of in situ production or of mechanical aggregation; perhaps both are the cause.

King and Hida (1957) show, on a relatively large scale, a relation between high standing crop of zooplankton and the frontal system in the central equatorial Pacific, without, however, establishing the actual cause of the high plankton values. They showed peak values slightly south of the three fronts studied. They also showed a somewhat lower quantity of zooplankton in the convergence zone (2° N.- 4° N.) than in the divergence zone (2° S. - 2° N.).

Beklemishev and Burkov (1958) showed that plankton is more abundant in the zone of contact between the Kuroshio and Oyashio than to either side and that this plankton comprises forms from both biotopes ((1) cool, low-salinity; (2) warm, high-salinity). The zone of mixing, however, is about four hundred miles wide in the area they studied. They say further, "The quantity of species in the zone of mingling of water masses sometimes turns out to be greater than each separately (Siomina, 1957)."[3]

[3]In their bibliography these authors do not refer to a 1957 publication by Siomina, but do refer to his 1958 publication, which seems to be appropriate to their statement, consequently, his 1958 paper is listed in the literature cited section of this paper.

Some results obtained by the staff of the Bureau of Commercial Fisheries Biological Laboratory, Honolulu, Hawaii, show catches of zooplankton in net hauls made within 5 to 10 miles of a front in the central equatorial Pacific. The highest catches were in the front and on the warmer side, about 5 miles away. The volumes caught 5 miles away on the cooler side and 10 miles away on the warmer side, were roughly equal, though significantly less than the above-mentioned highest volumes. Again, these data do not indicate the cause of the plankton distribution.

Knauss (1957), describing a front in the tropical Pacific (ca. 3° N., 120° W.), probably between South Equatorial Current water and Equatorial Counter-current water, says, "High biological activity was associated with the front; however, there was no floating debris. The cold water was relatively sterile; most of the life appeared to be concentrated in the relatively narrow frontal zone". The biological observations were made by persons using a dipnet only.

An oceanic front is named by analogy with an atmospheric front (p. 2). Doubtless the analogy does not end there, yet their similarities are general or remain largely unknown. Even so, one may speculate on whether atmospheric biota are affected by an atmospheric front in a way similar to the way oceanic biota are affected by an oceanic front. In this regard, a study by Sayer (1962) of the movements, over many days, of locust swarms in a major atmospheric front in Somaliland is most interesting. The locusts showed continued aggregation at the front. They were swept upward in the acute angle between the inclined interface of the front and the ground, and then glided downward only to be returned to the interface by the wind. In this spiralling fashion they moved slowly along the frontal axis.

In contrast to the relatively ill-substantiated idea that frontal systems are focuses of high standing-crops of zooplankton is the much better substantiated idea that some frontal systems are sites of relatively high abundance of pelagic fishes (Uda, 1953, 1954, 1959, 1961). Japanese fisheries for bluefin, albacore, and skipjack are closely related to the frontal system formed by the Oyashio and Kuroshio (Uda and Ishino, 1958); so is the whale fishery (Uda, 1938, 1954).

The frontal system between the Gulf Stream and the Labrador Current is not the focus of intense fishing such as there is off Japan. Nevertheless, yellowfin and bluefin tuna are strongly associated with the Gulf Stream front. Anonymous, 1959; Hela and Laevastu, 1962; Rivas, 1955; Laevastu and Rosa, 1963; Squire, 1963; Walford, 1958).

There is a major front in the Norwegian Sea where mature herring aggregate for feeding in summer, between spawning, (Devold, 1963). Eggvin (1940) describes the advance of a cold front of Baltic water through the Skagerrak northwards along the Norwegian coast in the early spring. This front, however, does not attract the herring but drives them offshore and out of their favored habitats in ways that vary from year to year, according to Eggvin.

Robins (1952) demonstrated a marked increase in troll catches of skipjack in a relatively weak front in the entrance to Storm Bay, Tasmania.

Relatively little detailed work has been done on oceanic frontal systems in spite of oceanographers' manifest interest in them. What has been done has been overwhelmingly physical and dynamical, and generally on a large scale (e.g., Gulf Stream studies). The literature has few quantitative biological measurements at fronts, especially the smaller, sharper ones, because such investigations are difficult to carry out.

The fronts studied by the STOR program have two points of general interest: (1) judging from the literature, they have been more comprehensively studied than any others (though not necessarily in any particular aspect); and (2) they occur in an area across which yellowfin and perhaps skipjack normally migrate, at a time of year when these fronts are best developed. These studies contribute to our knowledge of a relatively little-known phenomenon--the so-called Cape San Lucas front. This frontal system may influence the seasonal movement of tuna into the "local banks" fishery off the west coast of Lower California, though we do not know this.

A short review of the results presented in this paper was prepared, with a somewhat different emphasis, for the World Scientific Meeting on the Biology of Tunas and Related Species, held at La Jolla, Calif., in July 1962 (Griffiths, 1963).

OBSERVATIONS

Table 1 summarizes the main observations made; figure 1 shows the approximate location of the observations as well as the station patterns of STOR cruise TO-60-1 and part of CalCOFI cruise 6004-B. Complementary notes, some clarifying special difficulties, follow. Further information is given, where necessary, in the section "Results and Discussion." The original data will appear in a report on the above-mentioned cruises, and will include data on front 5 (TO-61-1).

Track

When observations were made close enough to land, bearings were taken on landmarks (mountains, points, lighthouses, etc.), but these bearings were accurate to no better than the nearest half-degree, which introduces small, unknown errors into the plotting of the ship's

Table 1.--Observations at fronts

Front	Date	Local time of day[1]	Feature studied or activity	Method of observation	Part of front - warm (w), middle (m), or cool (c) side	Observations, surveys, or casts (code in parenthesis)
	1960					Number
1.....	7 May	0750-1430	Track	D-r.[2] navigation; l.a.n.[3] fix	w, m, c	---
	7 May	0750-1430	Sea surface temperature	Thermograph survey	w, m, c	1
	7 May	1000;1035; 1150;1310	Surface currents	GEK jog[4]	w c	2 2
2.....	10 May	0750-1855	Track	D-r. navigation; l.a.n.[3] fix	w, m, c	---
	10 May	0750-1855	Sea surface temperature	Thermograph	w, m, c	1
	10 May	0800-0845; 0930-1020; 1115-1150	Temperature to ~100 m.; surface salinity (one pass only)	BT passes with surface water samples on one pass	w, m, c	3
	10 May	1250-1306; 1430-1451	Temperature, salinity, oxygen, phosphate, to ~ 200 m. deep	Hydrocast[5] - 10 Nansen bottles	w c	1 1
	10 May	1800; 1836	Surface currents	GEK jog[4]	w c	1 1
	10 May	1505-1540; 1705-1740	Zooplankton standing crop	Oblique, 1-m. net tows, to ~300 m. deep	w c	1 1
3.....	21 May 22 May	0105(21)- 1700(22)	Track	D-r.[2] navigation; a few bearings on land marks	w, m, c	---
	21 May 22 May	0105(21- 1700(22)	Sea surface temperature	Thermograph survey	w, m, c	1
4.....	23 May	0255-1900	Track	D-r.[2] navigation; l.a.n.[3] fix	w, m, c	---
	23 May	0255-1900	Sea surface temperature	Thermograph survey	w, m, c	1
	23 May	1500-1522; 1808-1827	Temperature, salinity, oxygen, phosphate, to ~ 200 m. deep	Hydrocast[5] - 10 Nansen bottles	w c	1 1
	23 May	1150-1205; 1315-1340; 1445-1455	Chlorophyll _a_ (as measure of phytoplankton standing crop)	Plastic sampler cast: samples at 0,25,40 m.	w m c	1 1 1

See footnotes at end of table.

Table 1.--Observations at fronts--Continued

Front	Date	Local time of day[1]	Feature studied or activity	Method of observation	Part of front - warm (w), middle (m), or cool (c) side	Observations, surveys, or casts (code in parenthesis)
	1960					Number
4.....	23 May	1605-1642; 1825-1900	Zooplankton standing crop	Oblique, 1-m. net tows, to ~300 m. deep	w c	1 1
	1961					
5....	19 Apr. 24 Apr.	0955(19)- 1105(24)	Track	Bearings on land marks; some D-r.[2], some radar	w, m, c	---
	19 Apr. 24 Apr.	0955(19)- 1105(24)	Sea surface temperature	Thermograph survey	w, m, c	2 (major ones)
	20 Apr.	2052-2229(20); 2313(20)- 0010(21); 0057-0339(21)	Temperature to 100 m.; surface salinity; phosphate, nitrate, nitrite, silicate (one pass only)	BT passes; surface water samples on all passes. Bucket temperature taken with each BT	w, m, c	3
	22 Apr.	B series: 1008-1030; 1140-1205; 1345-1410	Temperature, salinity, oxygen, phosphate, nitrate, nitrite, silicate, to 200 m. (E series) or 300 m. (B series)	Hydrocast[5] - 10 Nansen bottles	w m c	1 (B1) 1 (B2) 1 (B3)
	23 Apr.	E series: 1109-1131; 1405-1432; 1247-1310			w m c	1 (E1) 1 (E2) 1 (E3)
	21 Apr.	0539,0925, 1126	Surface currents	GEK jog	w	3
		0605, 0848, 1150			m	3
		0635, 0800, 1222			c	3
	21 Apr.	1504(21)- 0710(23)	Surface currents	5 m. parachute-drogues	m (toward warm side)	1
		1528(21)- 1715(23)			m	1
		1445(21)- 1755(23)	Currents at 50 m.	50 m. parachute-drogues	m (toward warm side)	1
		1604(21)- 0634(23)			m	1
	22 Apr.	1030-1045 1120-1135 1130-1315	Chlorophyll a (as measure of phytoplankton standing crop)	Plastic sampler cast: bottles at 0,25,40, 100 m.	w m c	1 (B1) 1 (B2) 1 (B3)
	23 Apr.	1500-1600	Special cast: turbidity every m. to 45 m. deep; chlorophyll a at 13 selected depths	α-meter at 0,1,2.... 44,45 m. Plastic sampler cast; bottles at 0,3,6,11,14, 16,22,25,29,34,39, 45 m.	m	1 (E2)

See footnotes at end of table.

Table 1.--Observations at fronts--Continued

Front	Date	Local time of day[1]	Feature studied or activity	Method of observation	Part of front - warm (w), middle (m), or cool (c) side	Observations, surveys, or casts (code in parenthesis)
	1961					Number
5.....	22 Apr.	2243-2268(22)	Zooplankton standing crop	Horizontal hauls: 1-m. net, surface	w	1 (D2)
		0103-0118(23)			m	1 (D3)
		0412-0427(23)			c	1 (D1)
	22 Apr.	1725-1755	Zooplankton standing crop in strata	Clarke-Bumpus 1 sampler above thermocline	w	1 (C1)
		1911-1941		1 sampler in thermocline	m	1 (C2)
		2105-2135		1 sampler below thermocline[6]	c	1 (C3)
	22 Apr. (A) 23 Apr. (F)	A 1912-0143, F 1925-1947,	Zooplankton standing crop	Oblique hauls: 1-m. net, to 300 m. or according to depth	w	1 (A1) 1 (F1)
		A 0253-0326, F 2019-2040,			m	1 (A2) 1 (F2)
		A 0421-0454 F 2125-2157			c	1 (A3) 1 (F3)
	22 Apr.	2150-2239(22)	Nekton standing crop	5- by 5-ft. nekton net haul	w	1 (D2)
	23 Apr.	0008-0057(23)			m	1 (D3)
		0318-0407(23)			c	1 (D1)
	23 Apr.	1110	Productivity	Surface water samples in 2 light bottles	w	1 (E1)
		1203		and 1 dark bottle, C^{14} inoculation,	m	1 (E2)
		1214		deck incubation for half solar day	c	1 (E3)

[1] Time zone is +7 for all fronts.
[2] D-r. = dead-reckoning.
[3] l.a.n. = local apparent noon.
[4] Jog: special course during GEK measurement.
[5] Hydrocast comprises BT's to 450 feet and 900 feet bucket thermometer reading, Nansen bottle cast.
[6] Sampler below thermocline failed to operate properly.

track. Otherwise, all tracks were plotted from dead-reckoning navigation.

On STOR cruise TO-60-1 the thermograph's sensory element was so mounted that the sea-surface (injection) temperature readings immediately became too high when the ship was hove to. Thus when stopped in the middle of a front, we could not be sure that the vessel was remaining in the middle, which explains the lack of observations in the middle of fronts 1 to 4 (TO-60-1). This difficulty did not arise at front 5 (TO-61-1).

The vertical distribution of temperature across a front was investigated by repeated, rapid lowerings of a bathythermograph (BT) to about 100 m. depth, while the ship slowly crossed the front (this operation is called a BT pass). The time between lowerings was from 2 to 5 minutes on the passes made at fronts 2 and 5.

Salinity

The Knudsen method was used on shore to determine salinities of water samples taken on TO-60-1 (fronts 1 to 4). Those for TO-61-1 (front 5) were made on board by salinometer (Paquette, 1958).

Temperature-Salinity-Thermosteric Anomaly

Whenever salinity and temperature were measured more or less simultaneously (hydrocasts and BT passes), δ_T, the thermosteric anomaly (Montgomery and Wooster, 1954), was computed from them. All data processing involving the relationship between these three quantities was done by means of special graph paper (SIO form 4.5) described by Klein in an unpublished manuscript (A new technique for processing physical oceanographic data).

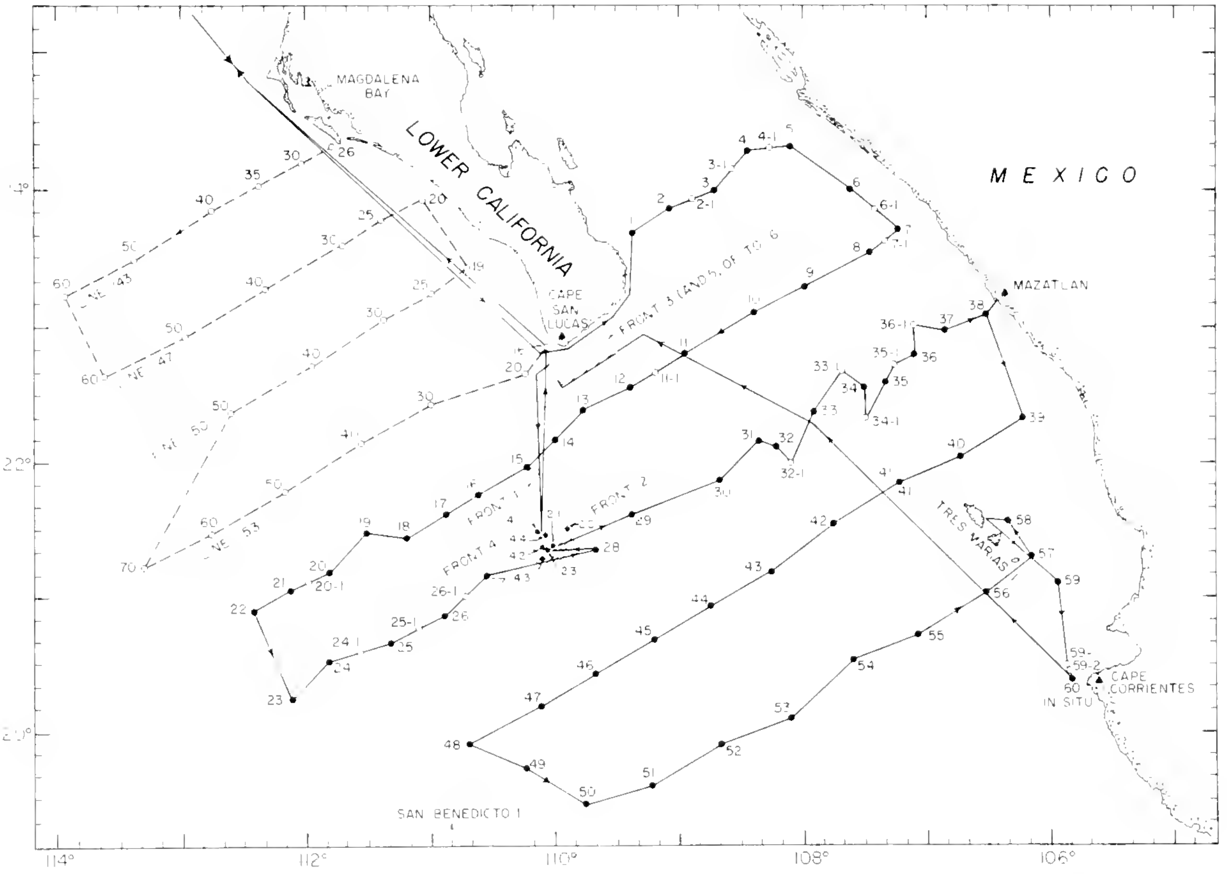

Figure 1.--Map of (i) track of STOR cruise TO-60-1 (May 1960), showing hydrocasts, including 10-m. bottle casts, (—•—), and between-station BT's (—o—); (ii) part of the track of CalCOFI cruise 6004-B (April 1960), showing full hydrocast stations (--o--); (iii) areas in which fronts were studied, including front 5, cruise TO-61-1 (April 1961).

Currents

At front 5, all parachute drogues were released in the middle of the front or slightly towards, but not in, the warm side.

At fronts 1, 2, and 5, geomagnetic electrokinetograph (GEK) measurements were made using a standard towing pattern (Von Arx, 1950).

Oxygen

The oxygen content of water samples taken on hydrocasts was determined on board by the Winkler method (Thompson and Robinson, 1939).

Inorganic Radicals

Phosphate, nitrate, nitrite, and silicate concentrations were determined by methods given by Strickland and Parsons (1960). Phosphate and, in consequence, silicate, determinations for TO-61-1 unfortunately were found faulty and were rejected. Only phosphate concentration was measured on cruise TO-60-1.

Chlorophyll a

The concentration of chlorophyll a in sea water (mostly as phytoplankton) was measured by the method of Richards and Thompson (1952).

Productivity

Productivity at the surface was measured by the C^{14} method of Steemann-Nielsen (1952). Samples was incubated in a deck incubator (Blackburn, Griffiths, Holmes, and Thomas, 1962, p. 8) for half a solar day. Time did not permit the collection and preparation of samples from different depths at different positions in the frontal system, sufficiently close to local apparent noon on the same day.

Water Transparency

Measurements of the coefficient of extinction of a beam transmission, α, were made at

several depths in front 5 (table 1), using an alpha-meter of 1-m. beam path length (Tyler, 1960). These measurements were made contemporaneously with chlorophyll a determinations, and at the same depths, as part of a special, independent study.

Zooplankton and Micronekton Standing Crop

For each oblique, 1-m. net tow (except for two tows in shallow water), 450 m. of wire were paid out at 50 m./min. and, after a pause of 1 minute, were taken in at 20 m./min. The ship's speed (1-2 knots) was adjusted to maintain a wire angle of about 45°.

All horizontal, surface, meter-net tows (on 50 m. of wire) at front 5 were made at night at a speed of 1-2 knots; differences between hauls due to effects of diurnal migration therefore were probably small.

Micronekton hauls also were made at night, when micronekton is generally most plentiful near the surface. The net used (Blackburn and associates, 1962) had a square 5- by 5-ft. frame at the mouth and was paid out on 350 m. of wire at 25 m./min. and hauled in at 10 m./min. Ship speed was 5 knots.

Miscellaneous

We noted the apparent abundance of easily observed fauna, such as marlin, turtles, and birds.

The weather and sea conditions were recorded periodically, though they did not change much on either TO-60-1 or TO-61-1.

RESULTS AND DISCUSSION

Kinds of Water Available to Form the Fronts

Before discussing the fronts, it seems desirable to provide an oceanographic context. The following paragraphs describe the kinds of water present in the general area, and their relationships.

Figure 1 shows the tracks of cruises TO-60-1 (May 1960) and 6004-B (April 1960) and the places where fronts were studied. Figure 2

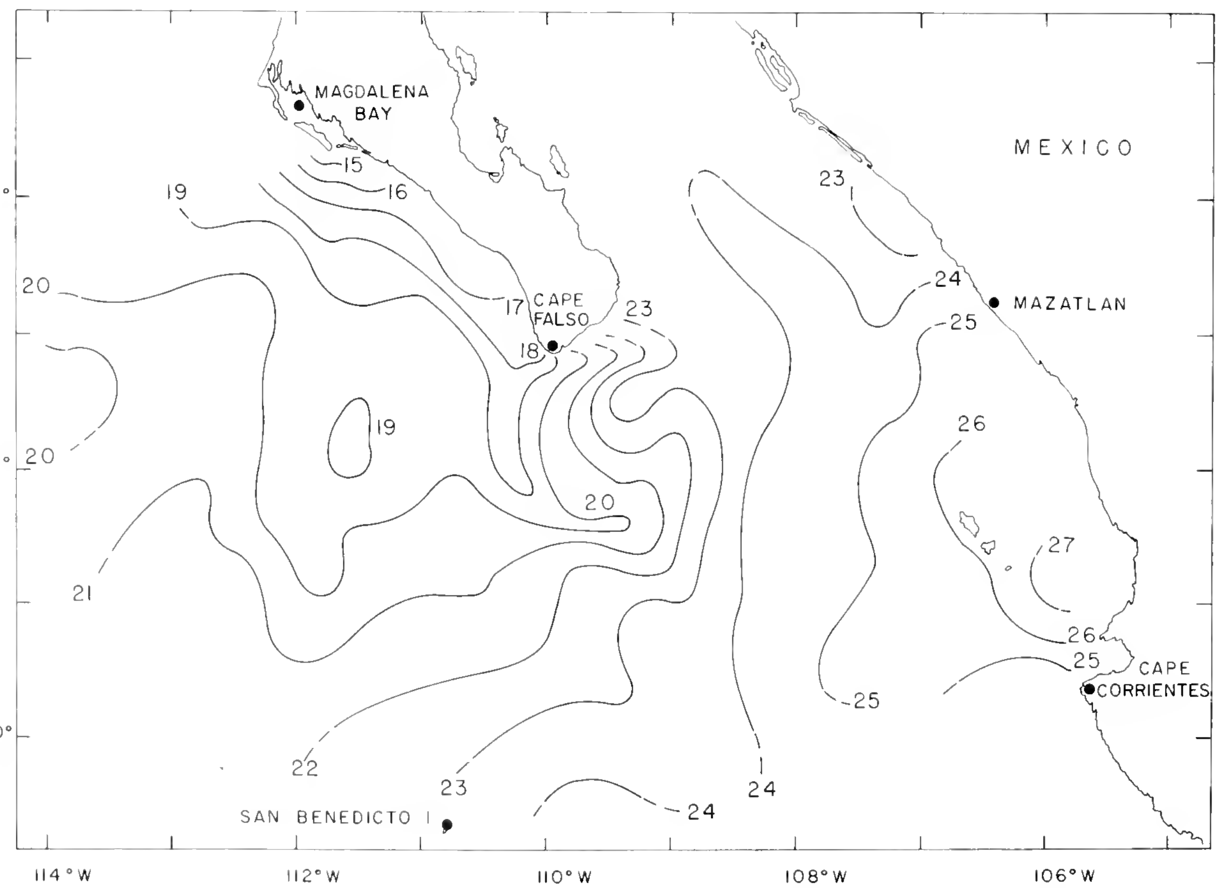

Figure 2.--Surface isotherm contours (interval 1° C.) from data of cruises TO-60-1 and 6004-B (CalCOFI). The approximate relation of the fronts to this distribution can be seen by comparing this figure with figure 1 (-•-•- speculative contour).

shows the distribution of surface isotherms from the data of the two cruises. Figure 3 shows the temperature profile, and figure 4 the salinity profile, from stations 7 to 22 of cruise TO-60-1. Because no hydrocast was made at station 15, the cool surface water was not detected by that method; it was detected by BT, however, and is shown in figure 3 by dashed contours (19^{o} and 20^{o} C. isotherms). The extensive oxygen minimum, typical of the eastern tropical Pacific Ocean, is superimposed on these profiles.

There are at least three kinds of surface water (upper 150 m.) off southern Lower California (Roden and Groves, 1959): (1) California Current water, from the north, flowing usually southeastwards off the western coast, cool and of low salinity (S ≤ 34.60‰); (2) equatorial Pacific water, from the southeast, flowing usually northwestwards, warmest and of intermediate salinity (S ~ 34.65 - 34.85‰) in the area of the Gulf entrance; (3) Gulf of California water, usually flowing out of the Gulf of California on its western side, somewhat cooler and more saline (S ≥ 34.90‰) than equatorial Pacific water. It is also possible that warm, relatively high salinity water from the central North Pacific intrudes into the area at the surface (Reid, Roden, and Wyllie, 1958; also p. 24, this paper). The Gulf of California is supplied mostly by eastern tropical Pacific water (Roden and Groves, 1959) and probably sometimes by California Current water (note the cell of low salinity at station 9, fig. 4). In the Gulf the temperature of the surface water is raised by insolation and its salinity is raised by evaporation (Roden and Groves, 1959).

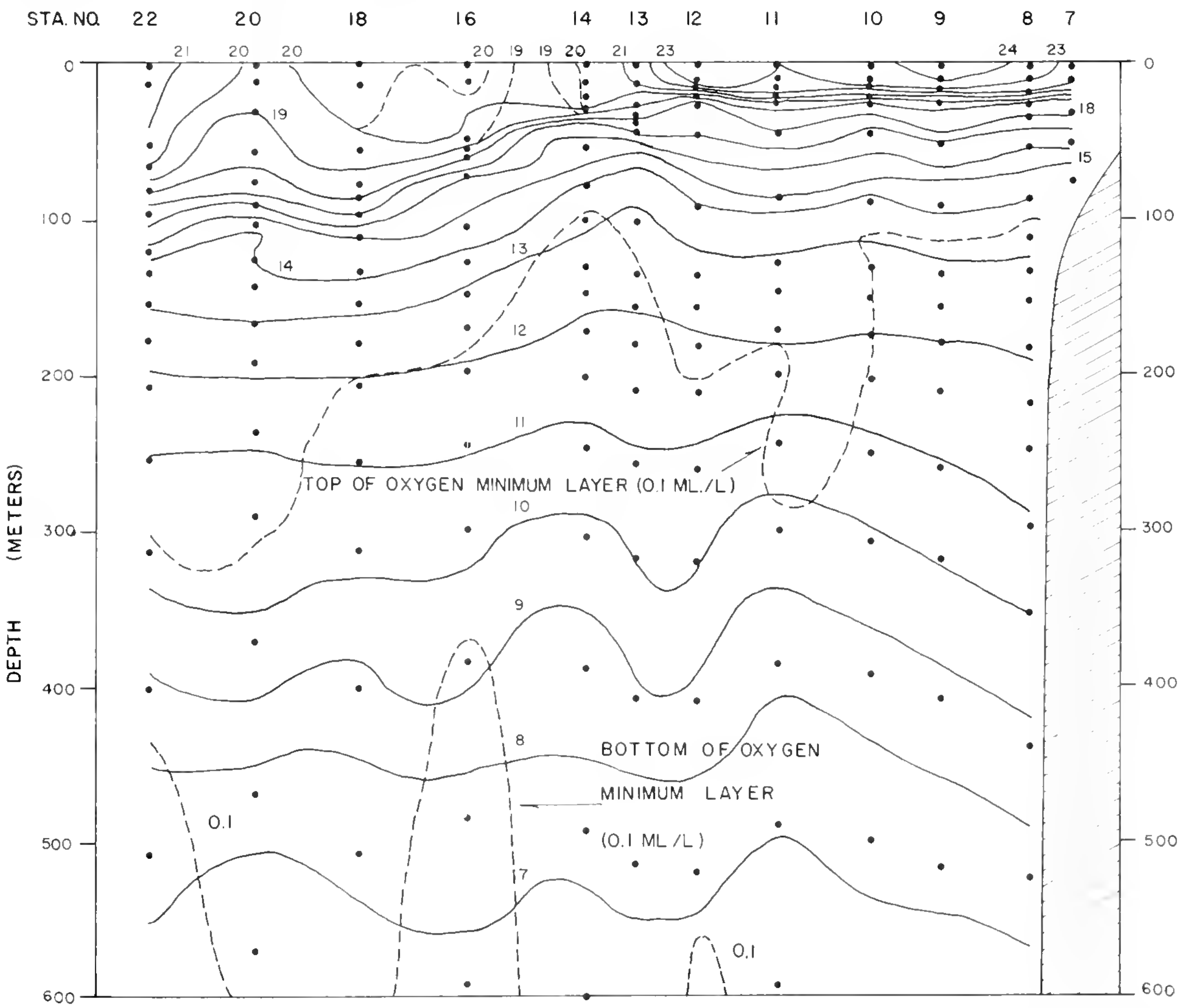

Figure 3.--Temperature profile to 600 m. based on data from hydrocast stations 7-22, TO-60-1; the dashed isotherms (19^{o}, 20^{o} C.) are from BT data and represent a feature not detected by the sampling pattern of hydrocast stations (figs. 1 and 2). Contour interval: 1^{o} C. Note the boundaries (0.1 ml. $l.^{-1}$) of the oxygen minimum layer.

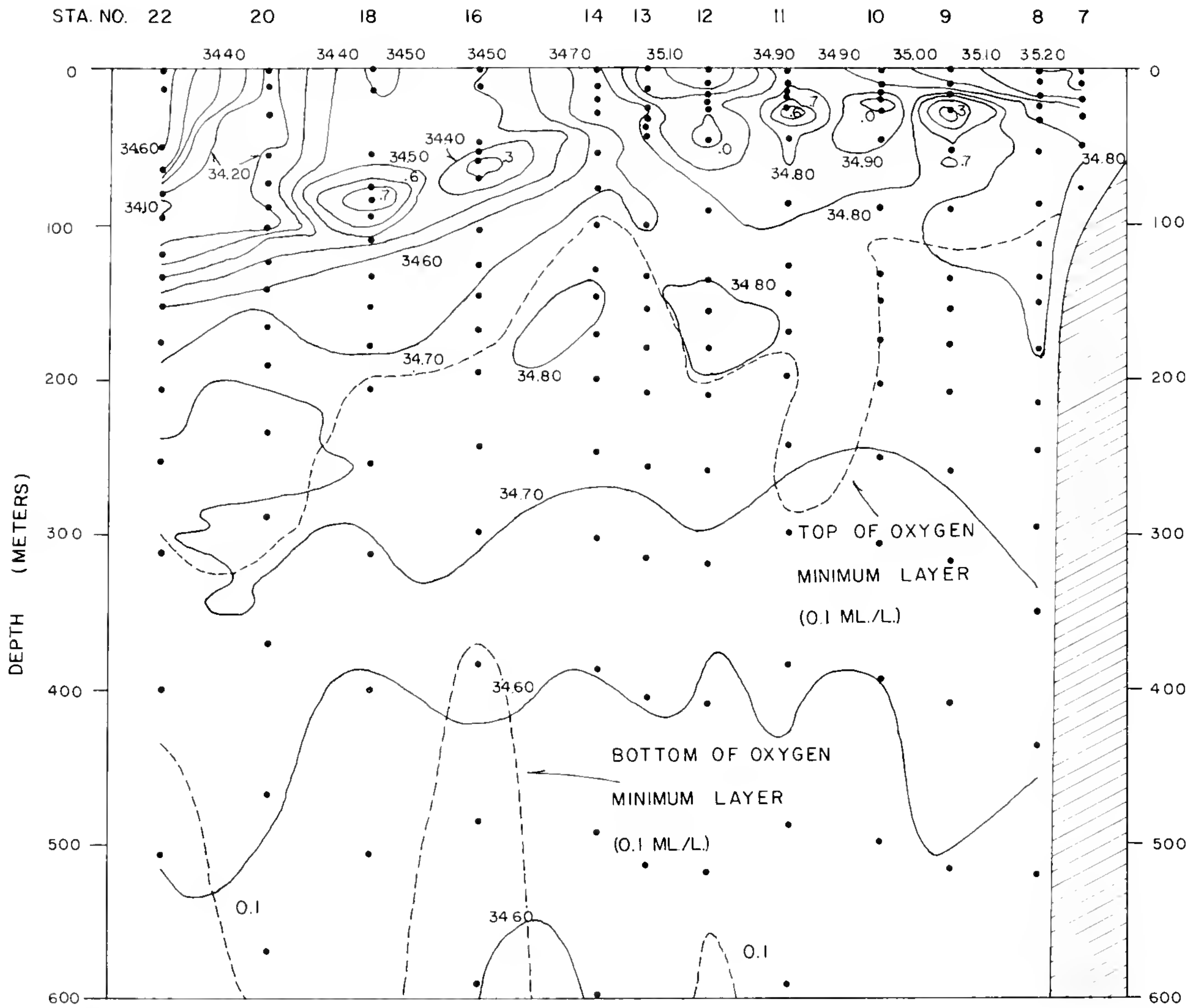

Figure 4.--Salinity profile to 600 m. based on data from hydrocast stations 7-22, TO-60-1. Contour interval: 0.10‰. Note the oxygen minimum layer, as in figure 3.

Figure 5 shows temperature-salinity (T-S) curves from several stations off western Lower California, from cruise 6004-B. Those from line 120 are of stations off Point San Eugenio (27° 50' N., 115° 10' W.); those from line 143 (fig. 1) are of stations further south off Magdalena Bay. These curves are typical of California Current water in that area. The curve of station 143.60 probably shows the influence of warm, saline eastern tropical, or, possibly, central Pacific water at the surface. Figure 6 shows curves from stations on line 153, still further south, and from cruise TO-60-1. These two figures illustrate the fact that with decreasing northern latitude the salinity minimum (a marker of California Current water) and the salinity maximum below it (a marker of eastern tropical Pacific water) have an increasing value, but that the general form of the curve is maintained; that is, the changes are quantitative rather than qualitative.

T-S curves from stations still further south fall into two main families or are quite anomalous by virtue of deriving from more than one kind of water. Figure 7 shows curves of stations from TO-60-1 that probably represent equatorial Pacific water (especially stations 54 and 56). Figure 8 shows curves of TO-60-1 stations in the Gulf of California that typify Gulf water (except that the curve for station 10 suggests admixture of less saline water at the surface) at this time of year (spring).

Generally, the California Current's southeasterly flow is reduced in the autumn, and warm, saltier, equatorial Pacific water (Reid et al., 1958, call it "southern" water) moves northwestwards, inshore, along the coast of southern Lower California. This corresponds

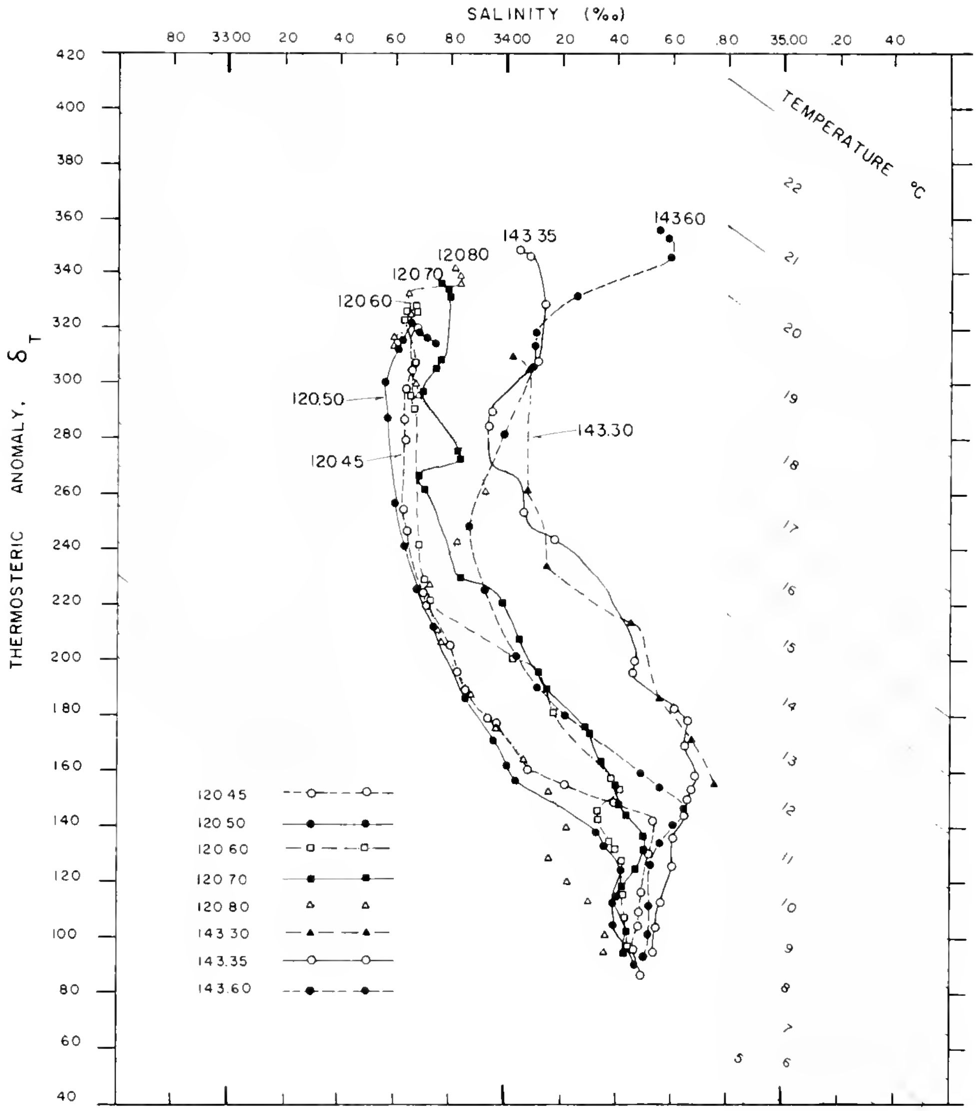

Figure 5.--T-S curves (on a δ_T field) of stations from CalCOFI cruise 6004-B. Curves from stations on line 120, off Point San Eugenio, are of "less transitional" California Current water than those from line 143, off Magdalena Bay, which are "somewhat more transitional." The curve of station 143.60 probably shows influence of central Pacific water at the surface.

to a period of reduced prevailing northwest winds and increased southeasterlies Great Britain, (Air Ministry 1956). Such a northwesterly countercurrent, though most pronounced at depth, is evident at the surface off southern Lower California between August and November (Cromwell and Bennett, 1959).

There is good evidence that Gulf surface water also contributes to this autumn countercurrent. Occasionally, surface salinities exceeding 34.80‰, at times reaching 35‰, occur inshore off southern Lower California, usually from about August to January. Salinities over 34.80‰ are not found in California Current water above a depth of about 125 m. so that upwelling would have to be particularly strong to bring water from the salinity maximum (150-200 m.) to the surface. Furthermore, upwelling is at a minimum at this time of year; nor do the isotherm distributions, corresponding to those of the isohalines showing high inshore values, indicate upwelling. In fact they generally show the northward flow mentioned (see CalCOFI data reports listed in literature cited section).

Surface salinities greater than 34.75‰ rarely are found in the eastern north Pacific Ocean, except near the Equator (Sverdrup et al., 1942, chart VI) and in the Gulf of California. Therefore, eastern tropical Pacific water, with its

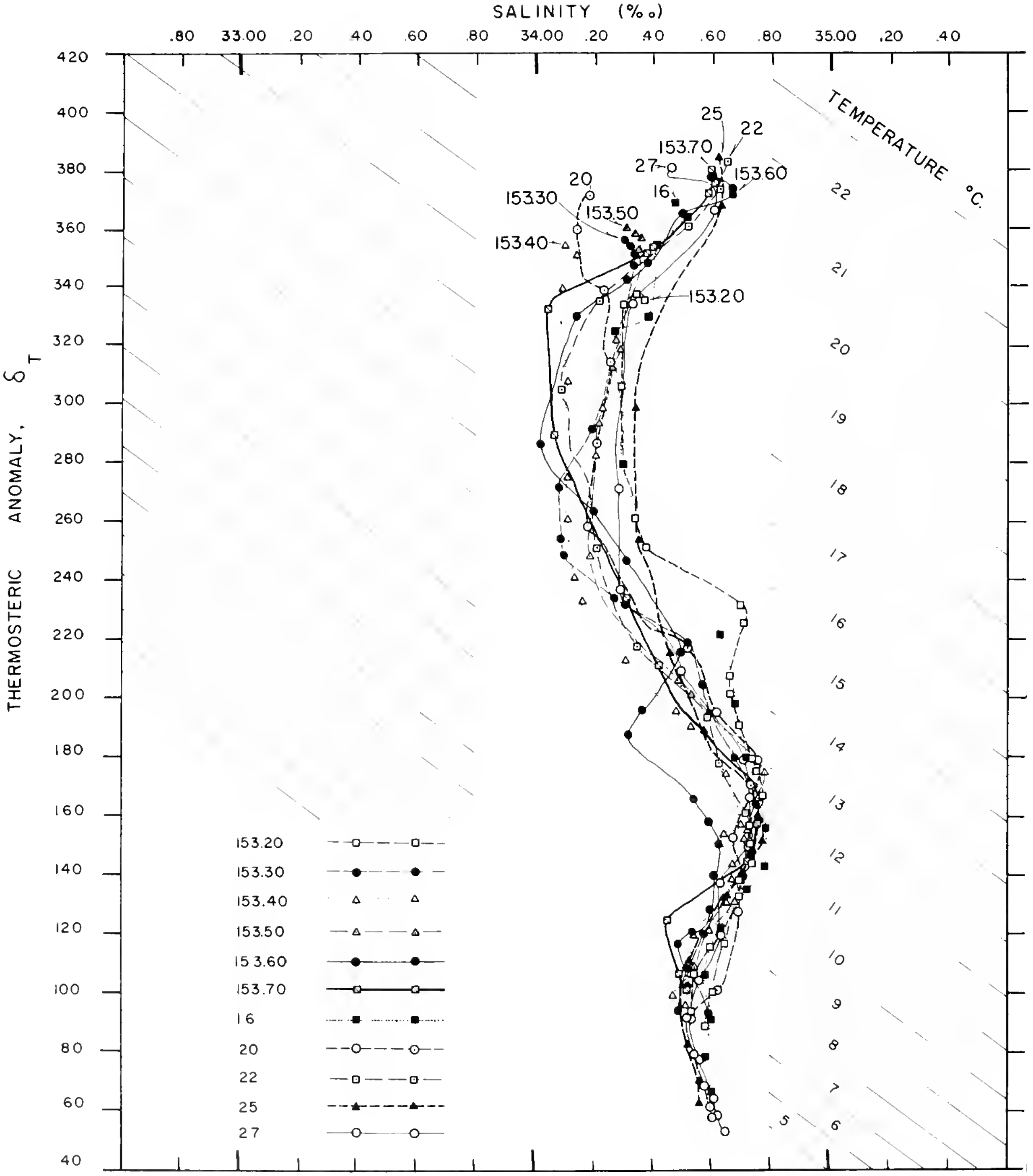

Figure 6.--T-S curves from stations on line 153 (cruise 6004-B) and five stations (16, 20, 22, 25, and 27) of cruise TO-60-1; these curves represent "most transitional" California Current water (fig. 5).

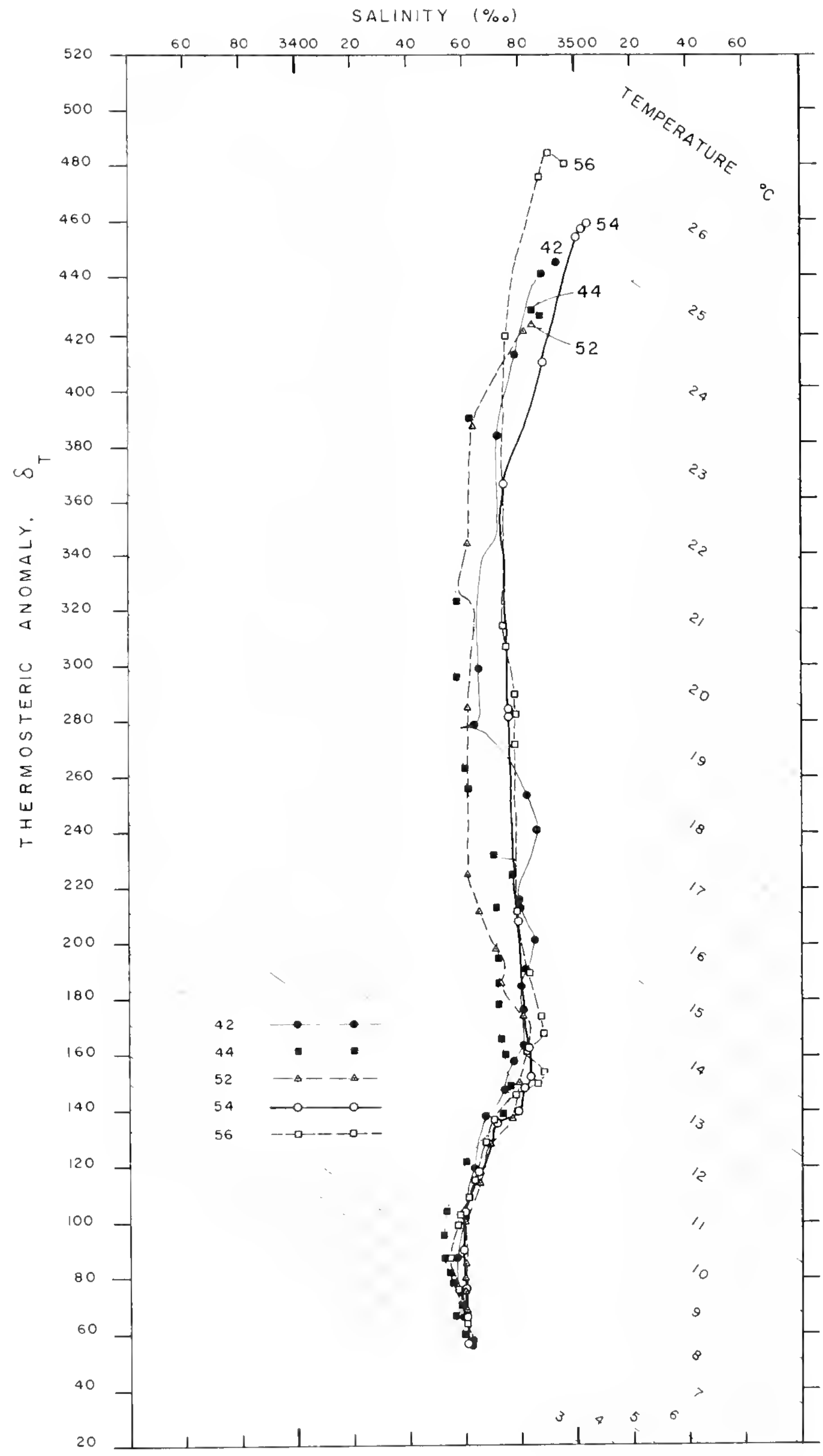

Figure 7.--T-S curves from several stations on cruise TO-60-1 that represent equatorial Pacific water near its northern limit (p. 26).

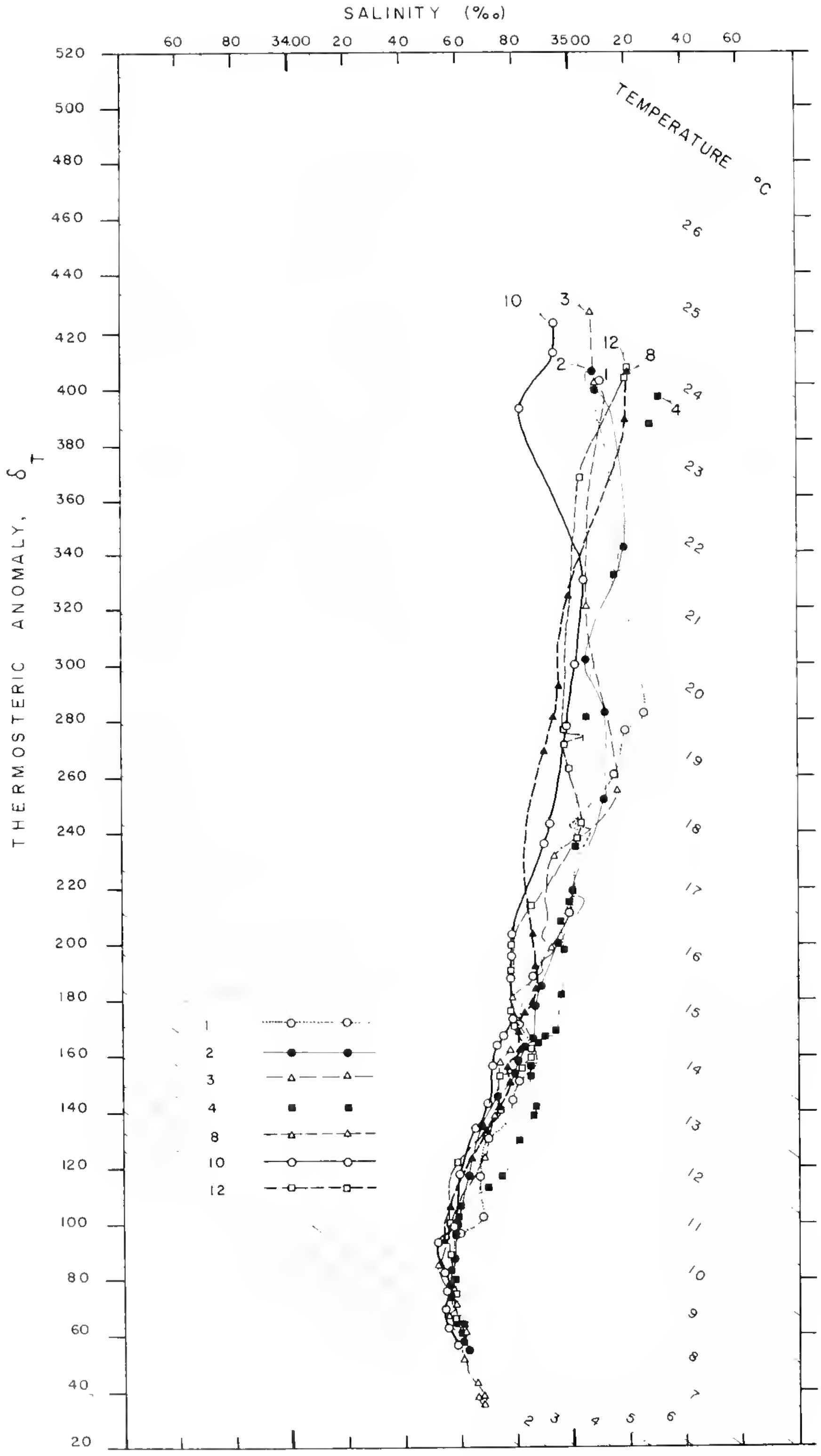

Figure 8.--T-S curves from several stations on cruise TO-60-1 that represent Gulf water. The curve of station 10 suggests the influence of water of lower salinity above the density surface of 360 centiliters ton^{-1}.

salinity maximum ($\sim 34.80‰$) at 150-200 m. depth, could not produce the high inshore surface salinities off western Lower California.

In situ evaporation, though at a maximum at the end of the year, is not great enough in this region to produce the observed salinities (Jacobs, 1951; Roden, 1959).

Reid et al. (1958) state that warm, saline ($\leq 35.00‰$) water from the eastern central Pacific is advected into the California Current on its western side, so that it can hardly be the cause of high salinities inshore, on the eastern side (see Reid et al., figs. 5b and 10a).

The most obvious and tenable view is that these high salinities are due to Gulf water which, with eastern tropical Pacific water, constitutes the autumn countercurrent. By early spring the northward countercurrent off western Lower California has ceased and southward flow resumes, with increased upwelling (compared with winter's) inshore; this strong upwelling continues throughout the summer.

For this area in spring and summer, the California Current water referred to throughout this paper is, therefore, a mixture of the somewhat more typical California water to the north (fig. 5) and some Gulf and eastern tropical Pacific water from the previous autumn and winter. For present purposes, I call it transitional California Current water. There is then the further complication caused by the upwelling of this water.

The frontal system shown in figure 2 is probably formed by the three main kinds of water alluded to, with the possibility that far out to sea it could be formed between the central Pacific water and eastern tropical Pacific water. The part of the system extending south from Cape San Lucas (or Cape Falso) is formed by Gulf and California Current water, and the part turning west from there (for example, near station 29, figs. 1 and 2) probably formed by eastern tropical Pacific and California Current water. No marked system is formed between the equatorial and Gulf waters in the eastern half of the Gulf entrance because the differences between these two kinds of water are small at the time of year being considered (spring). The small sharp frontal system often found at Cape Corrientes (Roden and Groves, 1959) would be formed by Gulf and equatorial water, but probably only when upwelling of the equatorial water is strong at Cape Corrientes (in April-June and, though less, in October-December, according to Cromwell 1958).

The fronts are not discussed in their chronological order but as follows: (1) front 5, the best studied (in April 1961), together with front 3 which was found in the same area but 11 months before (May 1960); (2) front 1 (May 1960); and (3) fronts 2 and 4 which were found in the same place, but 13 days apart, also during May 1960.

Fronts 3 and 5

Front 5, by virtue of the more detailed and varied study given to it, and because of its marked features, is discussed more fully than the others. Study of these others was more difficult because they were, except front 3, moving faster and were not formed of readily identified waters. Front 5 undoubtedly was formed at a boundary between water from the Gulf of California and from the California Current System. Even so, the California Current water was apparently partially composed of upwelled water (see below). Front 3, which was very similar to front 5 in its surface temperature distribution, was probably formed of the same kinds of water.

Surface temperature distribution.--The first phase of study at front 5, the initial thermograph survey, enabled us to plot the surface isotherm contours. These are shown, with the ship's track, in figure 9. The tongue of cool water protruding south and eastward round Cape Falso is probably upwelled (see below) inshore between Magdalena Bay and Cape Falso. It forms the front with the warm, saline water coming from the Gulf of California. This intrusion of cool water persisted for the period of the study (19-24 April), and intruded further eastward, according to the thermograph survey made at the end of the work. The surface isotherm contours from this latter survey are drawn in figure 10; judging from thermograph records made on the voyage from Cape Falso to San Diego, the origin of the cool water, mentioned above, is inshore north of Cape Falso, after upwelling. That upwelling occurs in this area at this time of year is shown by figure 2, as well as by many other CalCOFI data.

It is quite clear that even after 5 days the surface temperature distribution in the area was basically unchanged, though the obtrusions of cool water to the south and west, and of the warm water to the north and east, had elongated, causing the front to be aligned roughly parallel to the coast.

As were the rest, front 3 was found by thermograph. A thermograph survey indicated that the front was not strongly developed, and no further work was done. Plots of the corrected thermograph temperatures showed that a sharp front very probably existed directly between, roughly parallel to, two track lines (fig. 11).

There is an obvious similarity between the results of the thermograph surveys of front 3 and front 5. The cool eddy ($< 22.5^{\circ}$ C.) at front 3 appears to have been cut off from the remaining cool water to the north and west by the obtrusion of the warm (Gulf) water west of Cape Falso. Such a situation could be derived from the situations shown in figures 9 and 10.

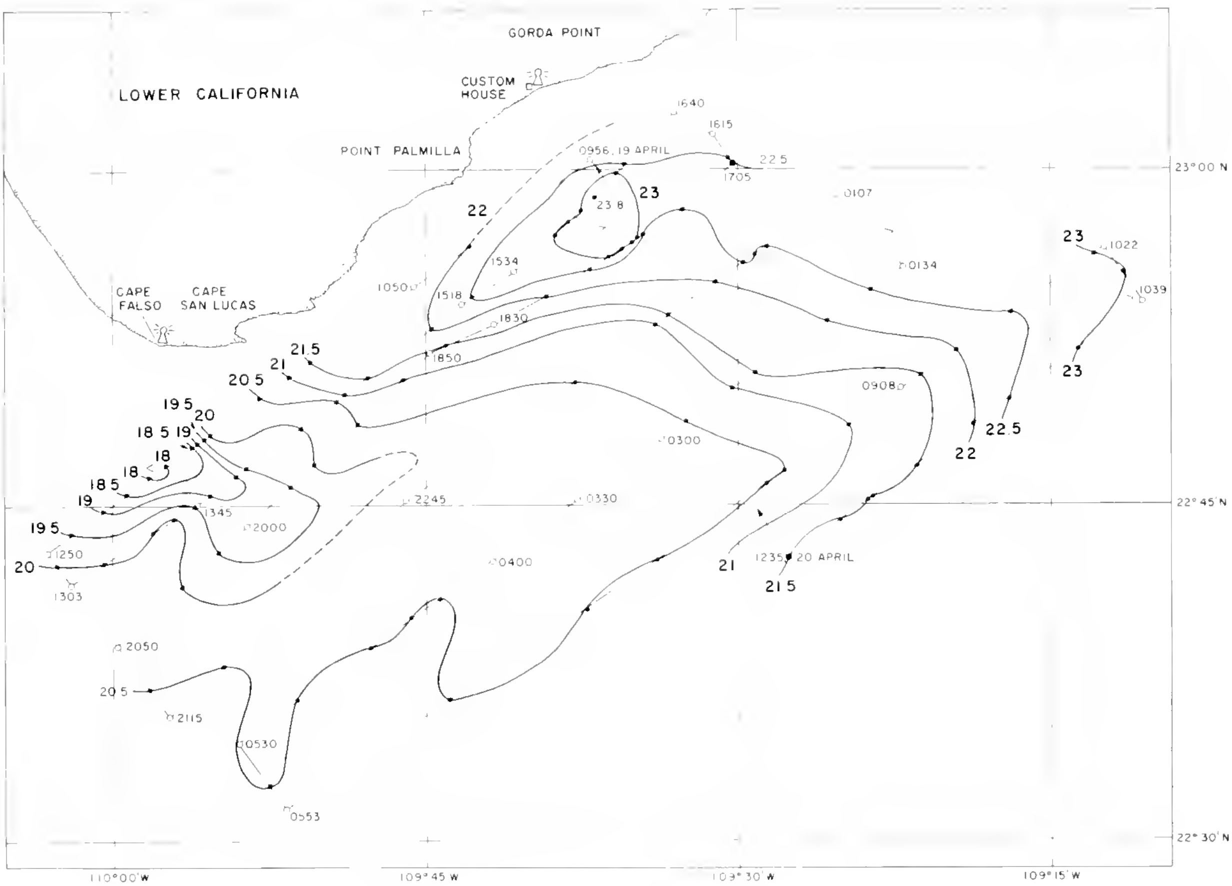

Figure 9.--Distribution of surface isotherms (contour interval: 0.5° C.) at front 5, off Cape San Lucas, Lower California, from the initial thermograph survey (0956 hours 19 April till 1235 hours 20 April 1961), the track of which is shown. -o- time check; -•- temperature check; ---- speculative contour.

There is some ground, then, for saying that the Cape San Lucas front (3, 5) is, at least in the months of March, April, and May, a fairly stable feature, and that it is oriented roughly parallel to the coast. All subsequent discussion in this section on fronts 3 and 5 refers entirely to front 5.

Surface currents.--As noted above, warm water was transported westward inshore and cool water was transported eastward further offshore. This transport was measured directly by drogues and less directly by GEK. It was also indicated by the ship which practically always drifted along an isotherm when hove to.

Figure 12 shows the apparent tracks of the four drogues released at front 5. The differences in the depths of the parachutes (5 m. and 50 m.) had no apparent effect on the flow pattern. The drogues were all, more or less, carried first northward then westward. Because they were all put in in the middle or slightly toward the warm side of the front, their apparent track is roughly as expected: northward round the end of the cool 'loop', then westward to Cape San Lucas. The drogues' paths agree roughly with the flow expected from the surface temperature distribution (assuming it reflects the density difference at depth): looking down the temperature gradient the geostrophic flow is to the right (westward mostly). Their average velocities were, reading from north to south in respect of starting positions, 11, 10, 13, and 15 cm. sec.$^{-1}$, slightly less than the average velocity based on GEK measurements (16 cm. sec.$^{-1}$).

According to GEK measurements, surface currents were somewhat across the isotherms (fig. 13). Two of the values were obtained in the cool water near the eastern end of the 'loop' in the front, indicating the easterly flow of the cool water. The remainder clearly indicated a flow of warm water from the Gulf. The GEK observations were a little northeast of the drogue paths. They showed a south-westerly surface flow in that area. Further west this outflow from the Gulf became westerly, according to the drogues. However, quite apart from the effects of the difference in location, there may be a difference between a drogue

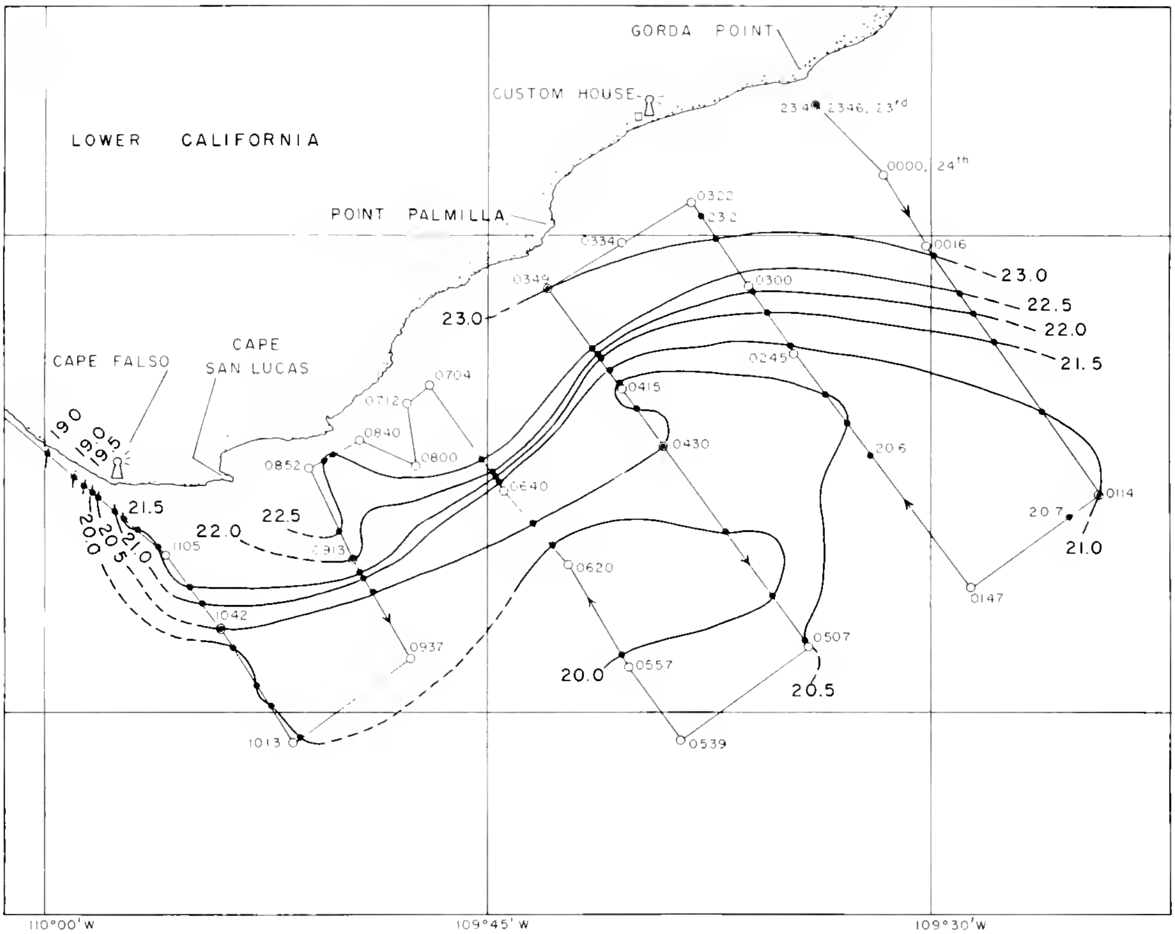

Figure 10.--Distribution of surface isotherms (contour interval: 0.5° C.) at front 5, off Cape San Lucas, Lower California, from the final thermograph survey (2346 hours 23 April till 1105+ hours 24 April 1961). -o- time check; -•- temperature check; ---- speculative contour.

track (an integrated datum) and a GEK measurement (an instantaneous datum) due to tidal motion (Reid, 1958).

Vertical temperature structure.--After the orientation and apparent direction of flow at front 5 were established by thermograph and GEK surveys (the drogues were set later), the vertical temperature structure was studied by making three BT passes. Although the results of all three passes were similar, two did not cover the complete range of surface temperature in the area of the front (fig. 14). The temperature profile derived from the third pass is given in figure 15.

The basic structural feature is a marked temperature inversion, apparently due to cooler water being underlain by warmer water. There is, however, no evidence of instability, according to the density profiles of this front (figs. 21 and 22). The presence of warm water within the cool appears as a complicated thermocline system. There is a fairly well marked thermocline at about 25 m. on the cool side of the front. It weakens toward the warm side, owing to the downward and horizontal extension of the warm water in the actual frontal zone. Well over to the warm side it becomes associated with another strong thermocline at about 35 m. on the warm side. This thermocline is strongest in the middle of the front, below the inversion zone; it persists to the cool side where its depth is about 75 m.

The front shown by the thermograph is a surface phenomenon, largely dissociated from the features just described. The 21°, 22°, and 23° C. isotherms, which alone intersect the sea surface in the BT profile, are not found in the inversion or in marked thermocline. Nevertheless, the two chief "frontal" isotherms (21° and 22° C.) do cut the surface directly above the inversion.

The "frontal layer" was defined by Cromwell and Reid (1956) as the transition zone between the warm water above and the cooler, denser water below. In effect, this is the thermocline between the water masses forming the front, and is to be distinguished from

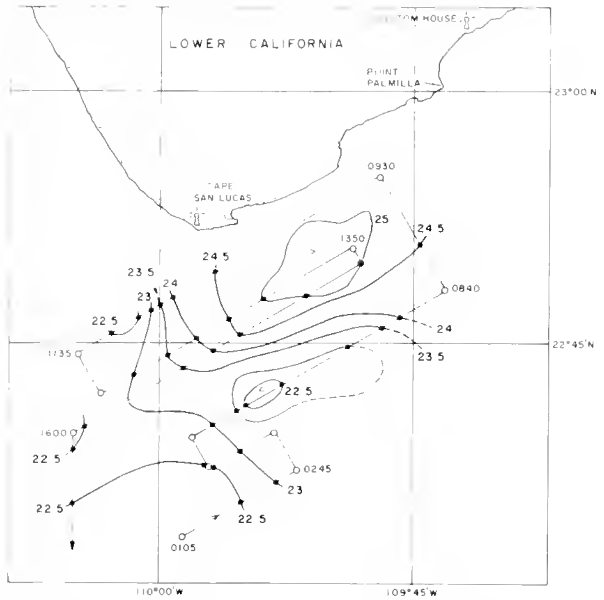

Figure 11.--Distribution of surface isotherms (contour interval: 0.5° C.) at front 3, off Cape San Lucas, Lower California, from a thermograph survey (0105 hours till 1600 + hours 22 May 1960). –o– time check; –•– temperature check; ---- speculative contour.

the true thermocline underlying the frontal water of both sides. Their results show that the frontal layer extended down from the sea surface first vertically then laterally. Such a layer is not obvious in the profiles we obtained. If the frontal layer is taken to be demarked by the 16°, 17°, 18°, 19°, and 20° C. isotherms, it assumes the general form of a letter Z, but it is least well-defined between about 25 and 60 m., the zone of the large inversion, and reaches the surface well to west of the front observed at the surface (fig. 9).

The five main cross-hatched areas (I - V) in figure 15 show water that is practically isothermal vertically; this follows the presentation of Cromwell and Reid (1956). In the fronts they reported on, however, there was presumed to be little salinity gradient, so that density was almost wholly determined by temperature; hence, they could hypothesize that vertical mixing would require least energy where water was vertically isothermal, and would be most likely to occur there. In front 5 there was also a marked salinity gradient (figs. 19, 20, and 25), so that such a hypothesis may not hold true.

The five main parcels of vertically isothermal water are: the surface water (I) and the deep waters (V); one corresponding to the warm water (III); and the other two (II and IV) corresponding to the cool water above and below the warm (III).

The starting positions of subsequent observations (hydrocasts, net tows) are given in figure 16. The temperature profiles derived from two hydrographic sections (B and E triplets of table 1; figs. 17 and 18) do not have the details of those from BT passes. The B series profile clearly shows the temperature inversion, but only in the 17° and 17.5° C. isotherms (fig. 17).

The absence of inversions in the 16°, 18°, and 19° C. isotherms in the B series profile, as compared with the BT section (fig. 15), may be due to two possible causes: (1) an evolution, by mixing, of the pre-existing situation, as shown by the BT section two days earlier; or (2) the middle cast (station 5B2) was so located in respect to the temperature structure shown in figure 15 (say at the position of BT no. 4), that only the inversion in the 17° and 17.5° C. isotherms was detected.

The temperature profile from the E series of casts (fig. 18) shows an inversion only in the 16.5° C. isotherm, which suggests a development, such as mixing, from the conditions of the previous day when the B series of casts was made.

Vertical salinity structure.-- The salinity profiles (figs. 19 and 20) from the hydrographic sections B and E give more definite information about the front below the surface. From salinity data of cruises TO-60-1 (May 1960), TO-61-1 (April 1961), and 6004-B (May 1960), and from eight CalCOFI cruises to this area in spring, it is safe to assume that the maximum salinity of California Current surface water in spring is about 34.60‰. The minimum salinity of Gulf water in the upper 100 m. at this time of year is about 34.70‰, the surface salinity being ≥ 35.00‰ (Roden and Groves, 1959). It therefore seems reasonable to consider, taking into account the salinity structure determined from the cast data, that the water between the 34.60‰ and 34.70‰ isohalines represents the boundary between the two kinds of water. The boundary, or front, is sharper at some depths than at others, being, perhaps, least definite near the surface and below 50 m. The "salinity front" at the surface roughly corresponds to the surface "temperature front". The isohalines between 34.60‰ (maximum surface salinity of California Current water) and 35.00‰ intersect the sea surface between the "middle" and the "warm" stations in both B and E series salinity profiles, as do two of three isotherms (figs. 17 and 18).

There is good agreement between the temperature inversion in the 17° C. isotherm (B series) and the salinity structure; the cool water in the inversion has a salinity of < 34.70‰, whereas the deeper, warm water has a salinity of > 34.70‰. The inverted isotherm from the B series is drawn as a dotted line on the corresponding salinity profile (fig. 19). The relation is not as good for the E series (fig. 20) because some mixing, marked by the presence of an inversion in the 16.5° C. isotherm only and by the reduced extent of the water of

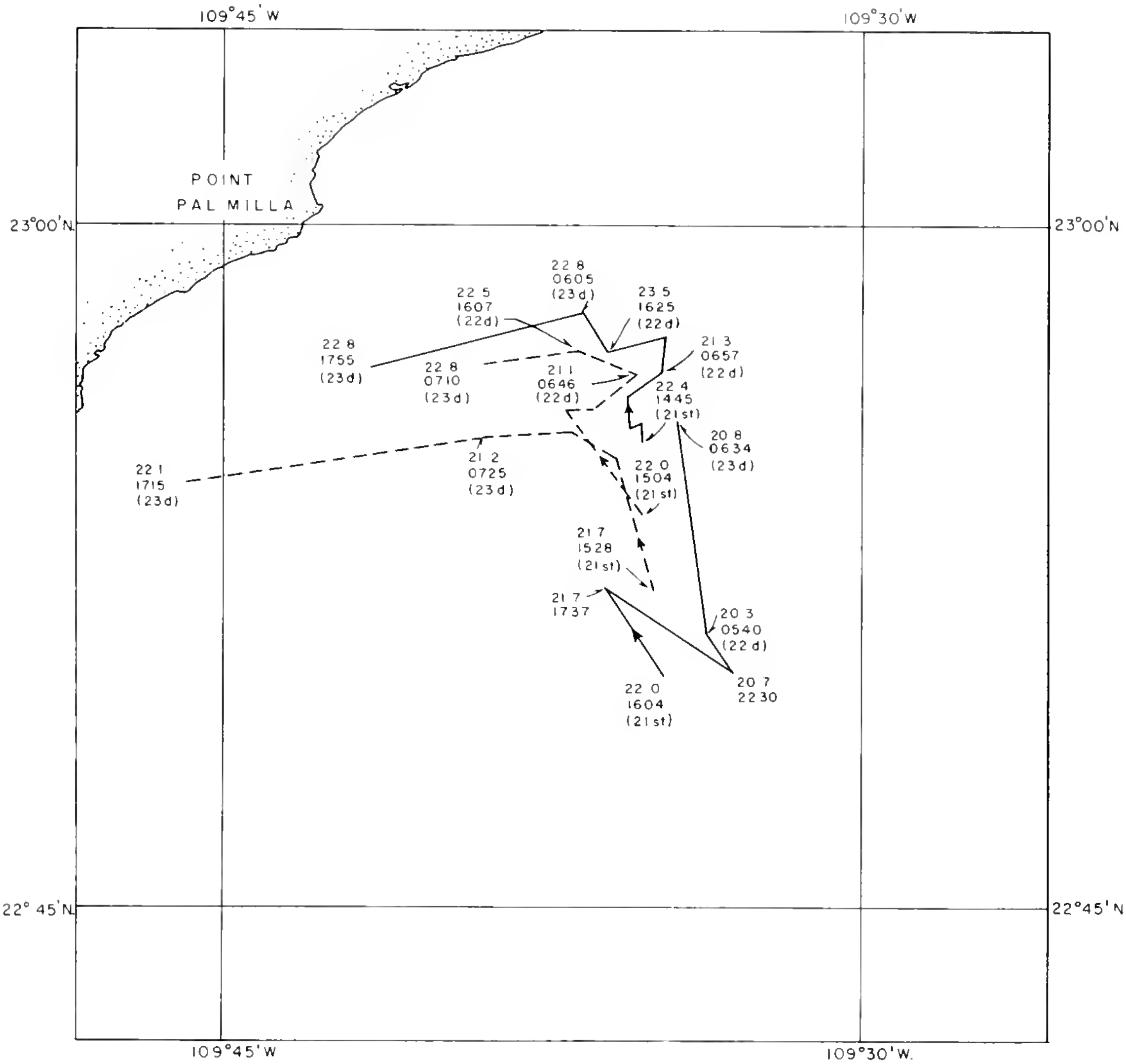

Figure 12.--Apparent paths of four drogues released in the middle or slightly on the warm side of front 5 on 21 April 1961. Track changes were based on subsequent sightings, the times of which are given where space allows. The temperature (°C.) of the surface water at time of sighting is also given. —►— drogues with parachute at 50 m. --►-- drogues with parachute at 5 m.

S < 34.50‰, has evidently occurred since the previous day when the B series of casts was made. The low-salinity tongue seems to have pushed further eastward into the high-salinity water, in spite of the fact that the E series of hydrocasts were west of the B series and were made a day later. We are, however, not absolutely certain of the exact relation of the casts to the front.

The salinity profile provides a fairly accurate description of the interface between the two kinds of water and agrees with the structure depicted by the data from the BT passes (fig. 15).

Thermosteric anomaly, δ_T.--The δ_T profiles of the B and E series of casts (figs. 21 and 22) are more or less similar to their respective temperature profiles (figs. 17 and 18). There is a sharp increase in the depths of some isanosteres (Montgomery and Wooster, 1954) near the "cool" station of the B series. This is true of the isotherms and leads to a strong correspondence, at the "cool" station (5B3), between the thermocline and the pycnocline. There is no inversion in the δ_T isopleths (isanosteres) for the B series because the temperature inversion is matched by a salinity inversion in such a way that a stable density

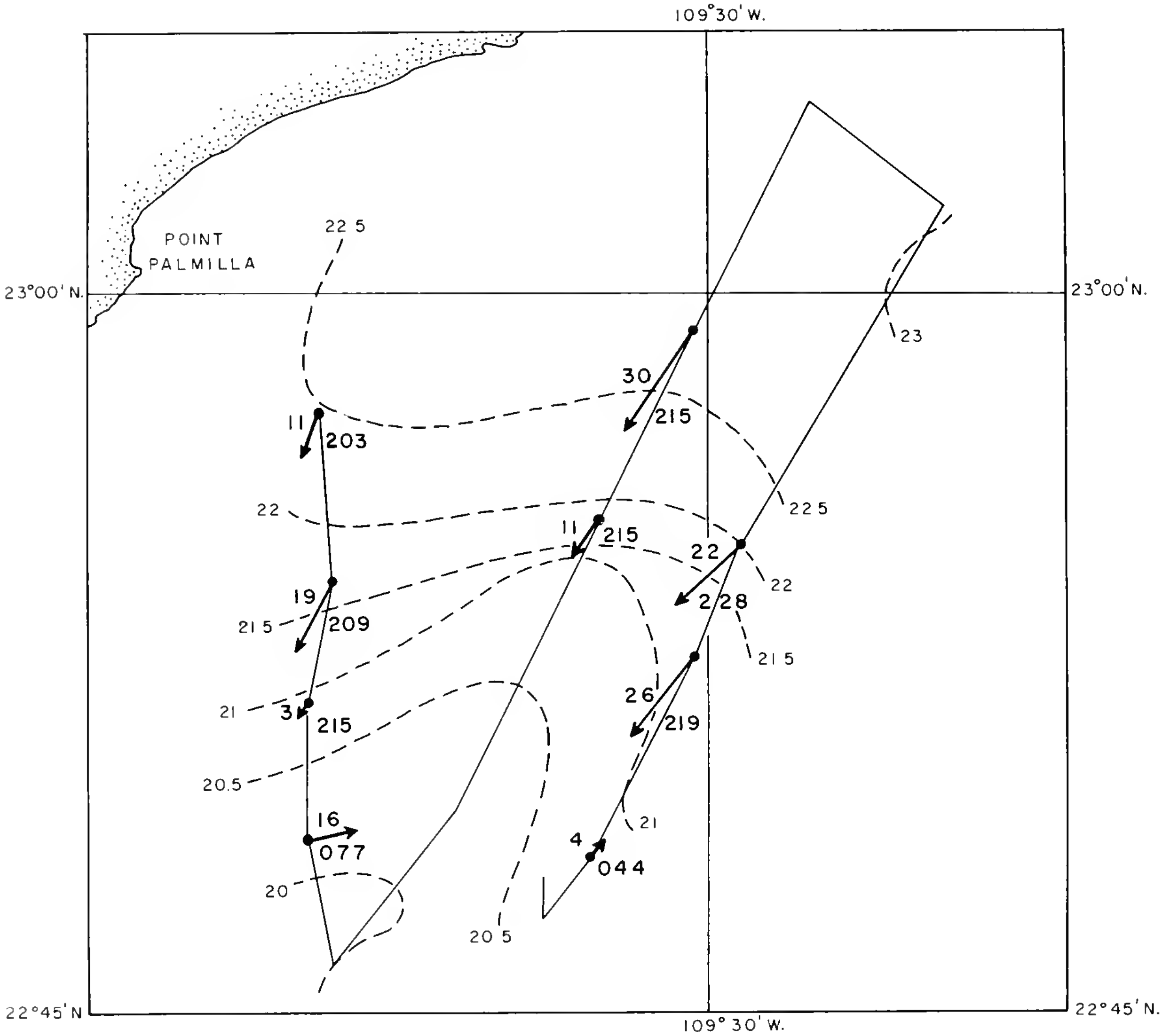

Figure 13.--Surface currents based on nine GEK measurements made on 21 April 1961. Currents are shown vectorially, the number above the vector being the velocity in cm. sec.$^{-1}$, that below being the bearing in ^{o}T. Superimposed are the track (———) and surface isotherms (– – – –, ^{o} C.) from the thermograph records.

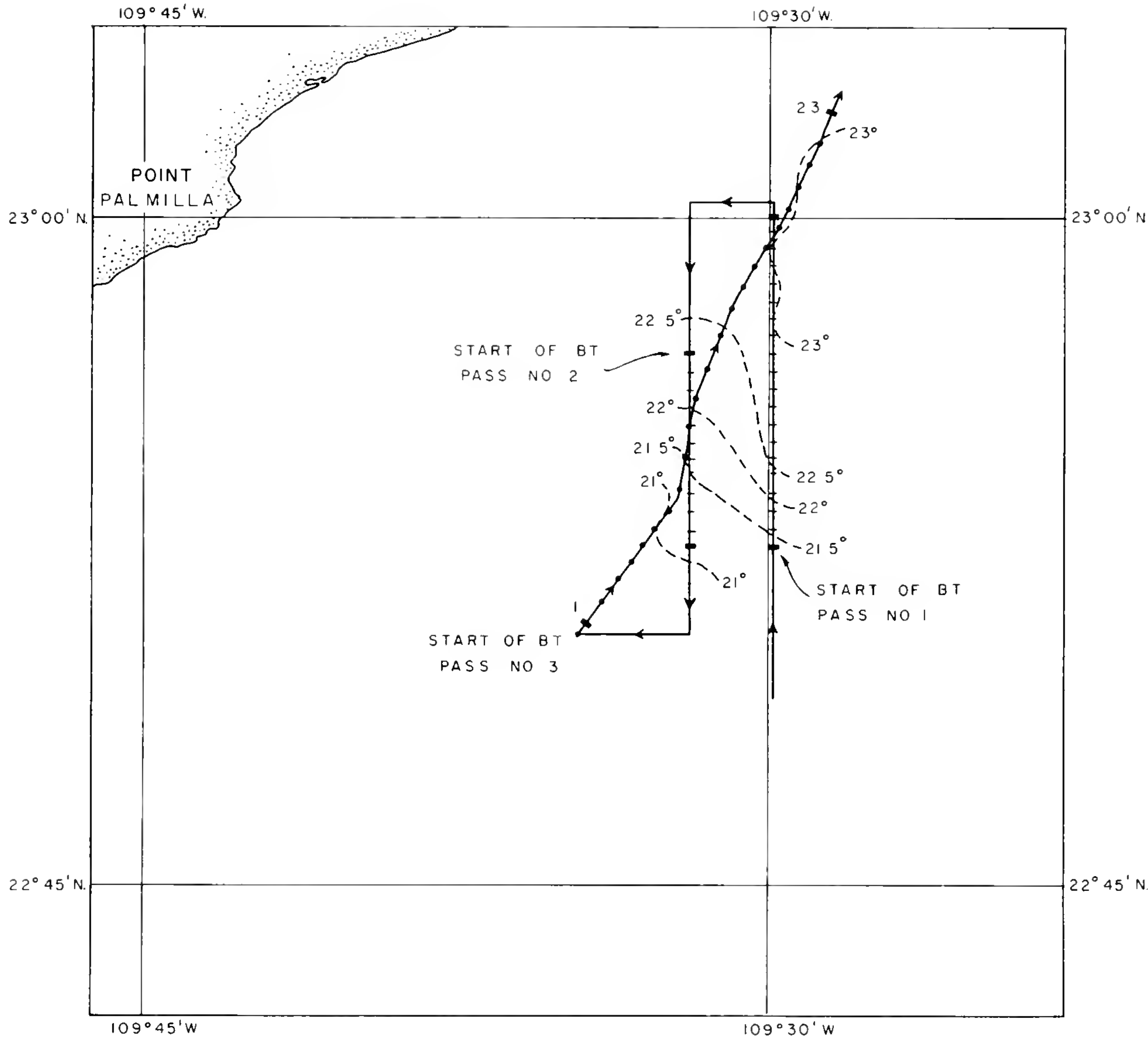

Figure 14.--Tracks of three BT passes made at front 5 on 20-21 April 1961. The third pass (—•—•—) is the one discussed in the text because it covers the greatest range of surface temperature, the isotherm contours of which are shown (---- , °C.).

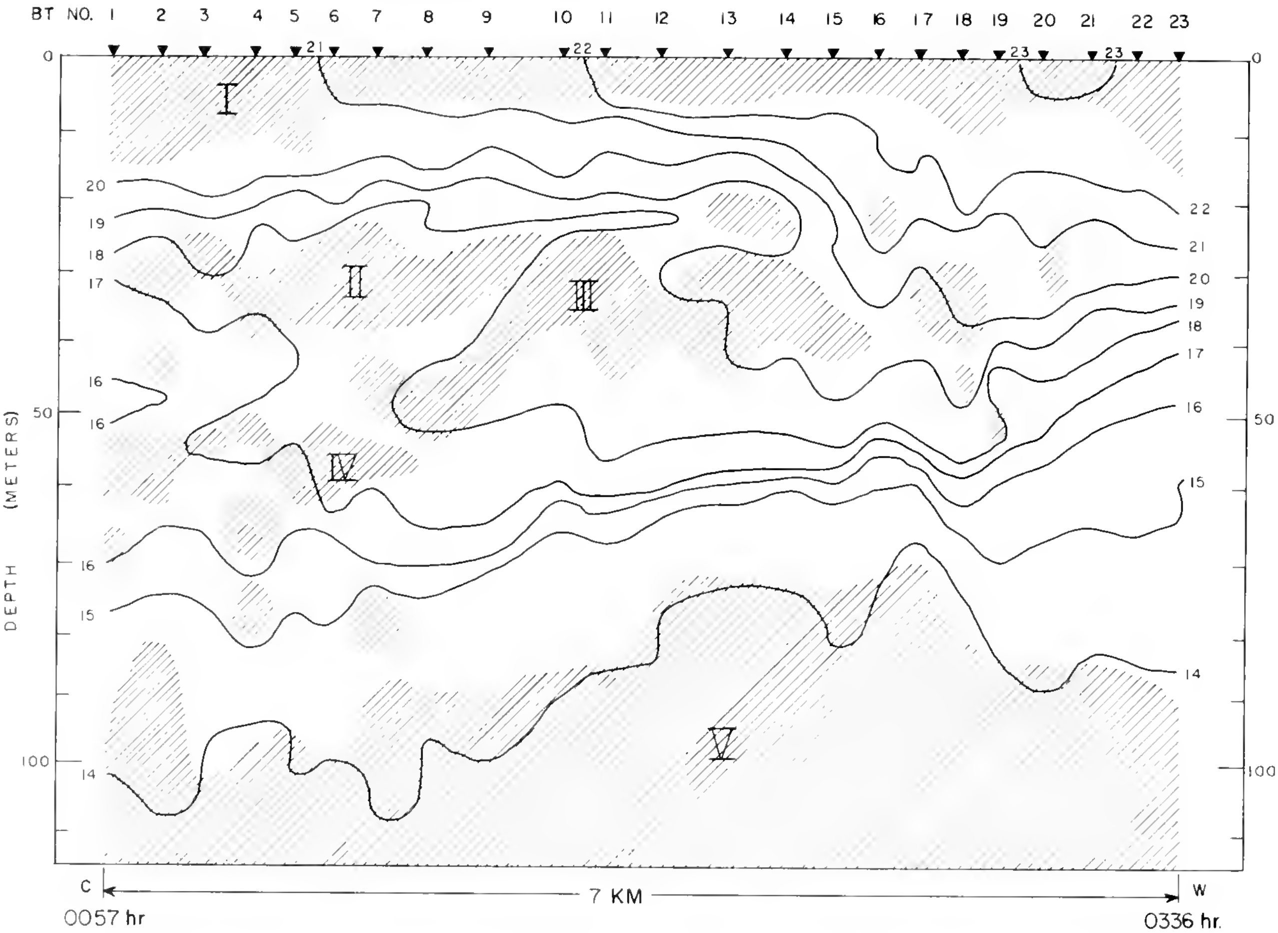

Figure 15.--The temperature profile from BT pass no. 3 across front 5 (21 April 1961). Cross-hatching shows water that is practically isothermal vertically. The five main bodies of such water (I - V) are discussed in the text. c = cool side; w = warm side.

distribution is maintained. There is also a stable density distribution for the E series.

<u>T-S - δ_T relationships</u>.--The complicated form of the interface points to a difficulty in studying such fronts. One cast was made on the warm side, one in the middle, and one on the cool side. Without prior information or the capacity to make a wider hydrocast survey, we supposed that the cast on either side would sample water of only one kind, either warm (Gulf) or cool (California Current) water, whereas the cast in the middle would sample a mixture of both. That this supposition was false is indicated in figures 23 and 24, which show T-S curves (on a δ_T field) for the three casts of the B and E series hydrocasts, respectively.

In figure 23, only the curve for the cool side (5B3) clearly fits into one of the three main families given in figures 5 and 6; it corresponds to California Current water. If one disregards the salinity minima between 15 and 35 m. and between 60 and 100 m., the curve for the warm side corresponds to a typical curve for Gulf water (fig. 8). The nature of these minima, caused by the California Current water, is evident in the salinity profiles in figures 19 and 20. The middle curve is similar to that of the cool water in the upper 25 m. and to that of the warm water below about 35 m. The zone between 25 and 35 m. is the interface between the two kinds of water which apparently are not well mixed, because the curve for the middle station does not lie between the other two. A similar argument holds for the E series curves (fig. 24).

Cromwell and Reid (1956) stated that a front was an abrupt density change; however, their observations were on temperature only. Knauss (1957) showed a density change of about 0.7 (for σ_t) or 70 cl. ton^{-1} (for δ_T) over about 300 ft. How much of a change, if indeed any, is necessary for a front to be maintained apparently has not been established. Taking Uda's (1959) definition of a temperature front as being between 0.5° C./10 miles and 5.0° C./10 miles (p. 2) and assuming no salinity

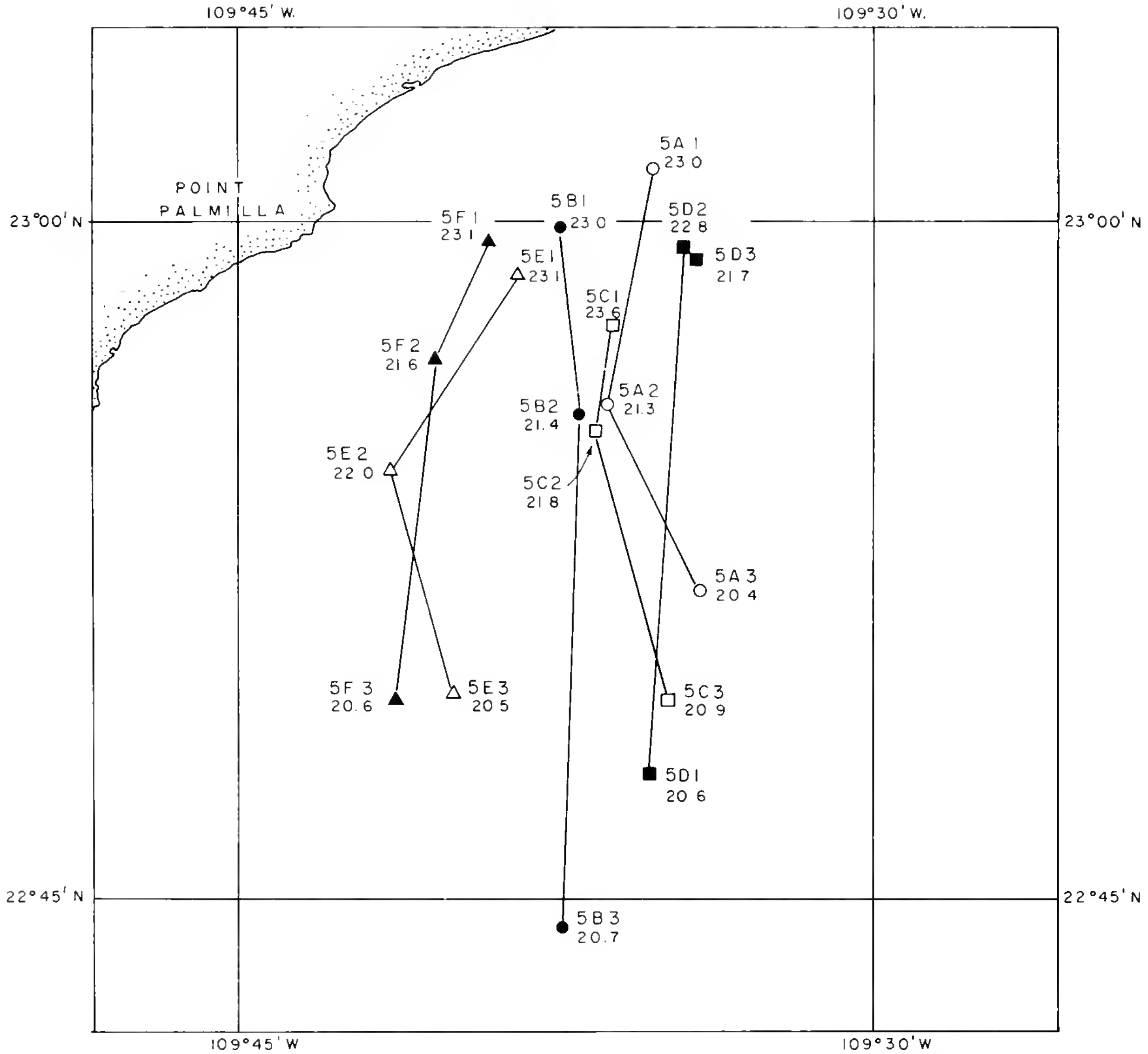

Figure 16.--Chart showing starting positions of hydrocasts (5B1-3; 5E1-3), oblique net tows (5A1-3; 5F1-3), nekton and surface net tows (5D1-3), and Clarke-Bumpus net tows (5C1-3). Surface temperature (°C.) at the start of an observation is given below the station number.

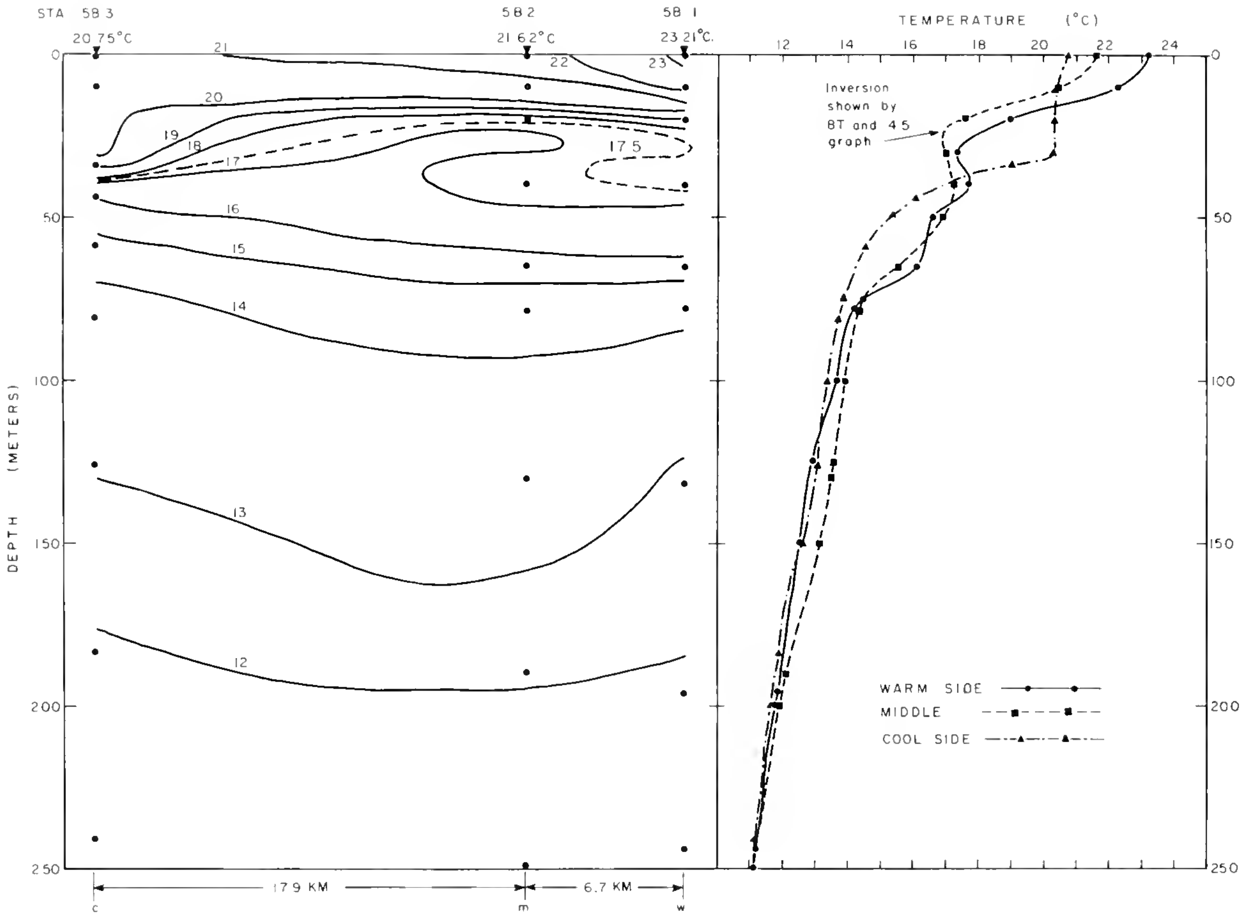

Figure 17.--Temperature profile and temperature-depth curves for the first (B) triplet of hydrocasts at front 5 (22 April 1961). c = cool side; m = middle; w = warm side; ▪ = Nansen bottle depths in profile.

change, we get a density range from 12 to 114 cl.ton^{-1}/10 miles between 15° and 20° C. and from 14 to 135 cl. ton^{-1}/10 miles between 20° and 25° C. The front at Cape San Lucas had a density difference across it at the surface ranging from 88, on the BT pass, down to 14 cl.ton^{-1}/10 miles on the E series hydrocasts (see text table on p. 25, and figs. 21, 22, and 25), well within the range suggested by Uda's figures. The fronts studied by Cromwell and Reid, and by Knauss, apparently had greater density differences across them at any given depth.

In the B series (fig. 23) the density differences across the front are much more pronounced at some depths than at others, but in any case are small below 50 m. In the E series (fig. 24) the differences are much smaller but are the smallest between 75 and 100 m. These facts suggest that mixing had taken place during the lapse between the two series of hydrocasts, but had not extended noticeably below 75 m.

Because the Cape San Lucas front clearly persists throughout spring and summer, one might suggest that the products of mixing of its constituent water masses are removed from the area. This might partially explain the reduced sharpness of the frontal system with increasing distance from Cape San Lucas (fig. 2). With respect to density gradient, front 5 differs from fronts 2 and 4 which are discussed later (p. 46 and 48). If a density discontinuity is a prerequisite for the formation and persistence of a true front, fronts 2 and 4 are more typical than front 5.

T, S, δ_T distribution at the surface on a BT pass.--At each BT lowering, we measured the sea-surface temperature by bucket thermometer and took a surface water sample for salinity determination; we then computed the δ_T values. The values of these three principal properties (T, S, δ_T) at each BT across the front during the third BT pass are shown in figure 25. We computed the gradients as

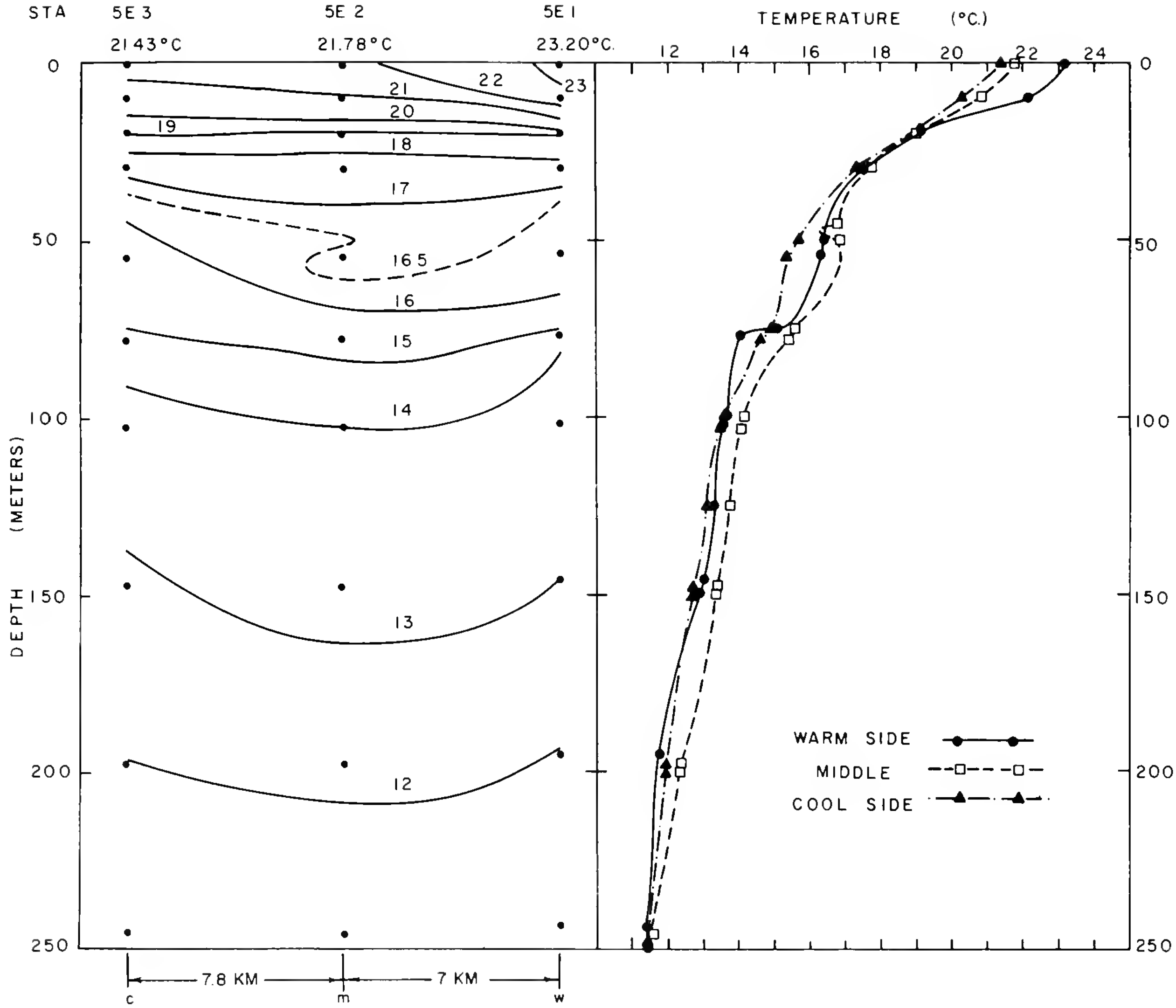

Figure 18.--Temperature profile and temperature-depth curves for the second (E) triplet of hydrocasts at front 5 (23 April 1961). c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

follows: the minimum value on the pass was subtracted from the maximum value, and this difference was divided by the distance between the two BT's to which the maximum and minimum corresponded. Where alternative choices of BT's are possible (e.g., salinity is same at BT's 4 and 5) gradients have been arbitrarily maximized by choosing the lesser distance.

The gradients are:

Property	Gradient	BT's
Temperature	0.43° C. km.$^{-1}$.	1 - 21
Salinity.	0.12‰ km.$^{-1}$.	5 - 18
Thermosteric anomaly . .	5.5 cl. ton^{-1} km.$^{-1}$ . . .	1 - 21

Oxygen distribution.--Above the mixed layer, oxygen is more or less at saturation level and its distribution is mainly determined by the temperature distribution: the cooler water has a higher dissolved oxygen content than has the warmer water.

Some of the oxygen isopleths deepen rapidly near the "cool" station in the B series profile (fig. 26), as do the isotherms and isanosteres. The 2, 2.5, and 3 ml.l.$^{-1}$ isopleths become relatively widely separated between 35 and 65 m. depth at the "middle" and "warm" stations. This zone of separation corresponds more or less to the inversion zone which may also be referred to as the mixing zone, because the temperature gradients are weakest in it (fig. 15).

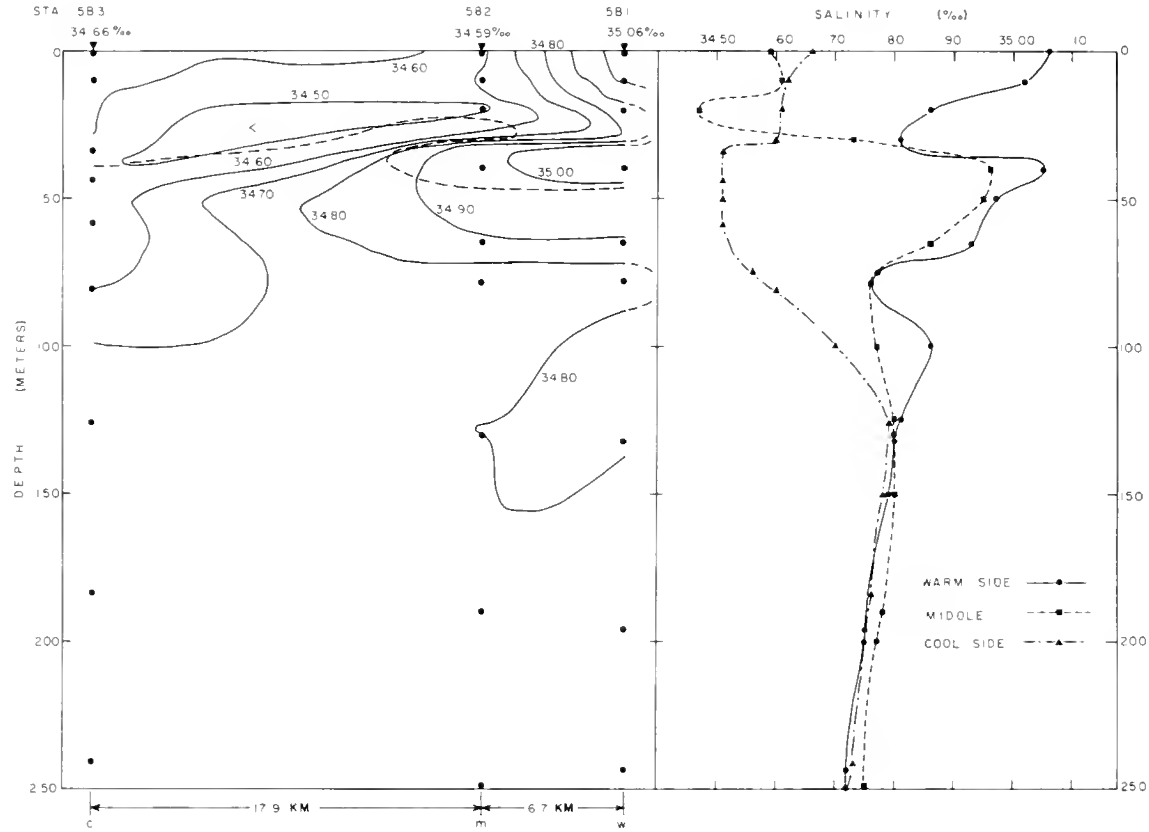

Figure 19.--Salinity profile and salinity-depth curves for the first (B) triplet of hydrocasts at front 5 (22 April 1961). The dashed line on the profile is the corresponding 17° C. isotherm contour (fig. 17), to show the relation of the temperature inversion to the salinity inversion. Note the salinity maximum (>34.80‰) of eastern tropical Pacific water at about 125 m. c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

The separation of isopleths between about 30 and 45 m. depth in the E series profile (fig. 27) may be related to prior inversion and to mixing, as was suggested for the isotherms of this triplet of casts (p. 18); the values are higher than on the previous day (compare figs. 26 and 27). The O_2-depth curve for the middle station in the E series shows much higher values, relative to those of the other two stations down to about 100 m., than does the "middle" curve in the B series. This may be due to oxygen having been mixed obliquely downward from the surface.

In both oxygen profiles there is some suggestion of a double "oxycline" corresponding to the dual thermocline previously mentioned. The two, at about 70 and 25 m. on the warm side (B profile), join at about 45 m. on the cool side. These values agree well with the apparent thermocline topography in the BT-pass temperature profile (fig. 15). Such agreement is not so well marked in the E profile.

Nitrogen as nitrite and nitrate.--Before trying to associate the distributions of phytoplankton (as chlorophyll a) with that of the zooplankton, some incidental chemical observations will be briefly discussed.

As noted earlier, phosphate and silicate determinations had to be rejected.

The nitrite profile of the B series (fig. 28) shows that station maxima correspond roughly to the thermocline and the pycnocline (figs. 17 and 21). The profile maximum, on the warm side at about 20 m., is shallower than the salinity maximum (~40 m.) and corresponds to the zone between the middle (5B2) and the warm (5B1) stations and between about 20 and 35 m. depth, a zone in which there is a well-developed salinity gradient (fig. 19).

Much the same is true of the nitrite profile of the E casts (fig. 28), except that the station maxima are a little deeper (as also is the salinity maximum) and, perhaps owing to mixing continued from the previous day, more

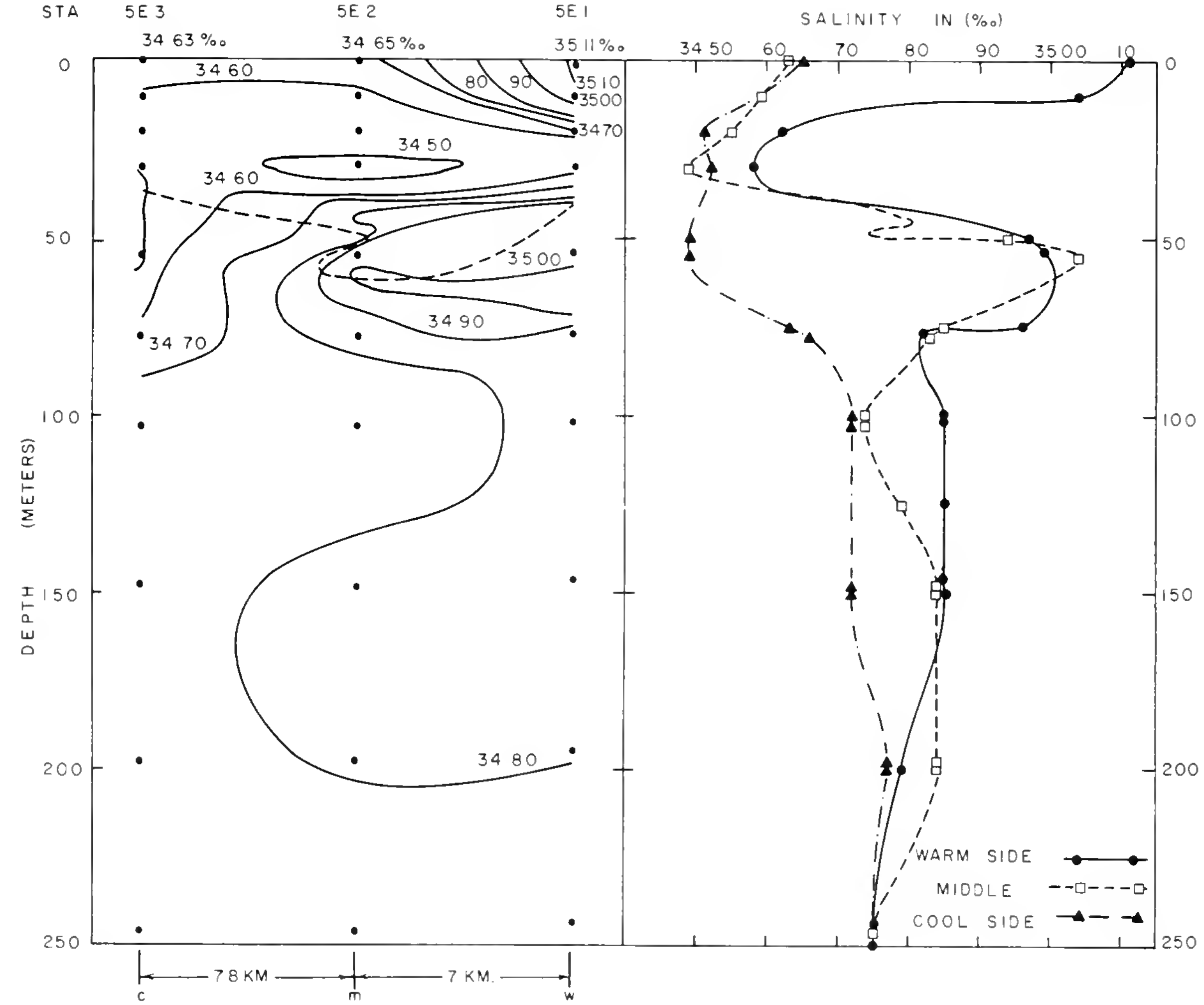

Figure 20.--Salinity profile and salinity-depth curves for the second (E) triplet of hydrocasts at front 5 (23 April 1961). The dashed line on the profile is the corresponding 16.5° C. isotherm (figs. 18 and 19). Note the salinity maximum (>34.80‰) of equatorial Pacific water at about 150 m. c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

similar to each other than are those of the B series profile. Immediately below the nitrite maximum, in both series of data, the water has a low oxygen content which is inversely related to the value of the nitrite maximum at each station (e.g., at station 5E2 the nitrite maximum is low while the oxygen content is relatively high; compare figs. 26 and 27 with 28).

There is a marked nitrite maximum at about 250 m. on the cool side. Such a maximum is found in samples taken between lat. 21° N. and 8° N. (Brandhorst, 1959). It is associated with the oxygen minimum of the eastern tropical Pacific waters (Brandhorst, 1959) and to some extent with the salinity maximum of those waters, as Brandhorst's appended data show but to which he does not draw attention. It is surprising here, however, that this deep maximum is found only on the cool side of the front which would be the side less expected to have it. The maximum does not occur in the E series profile, and the possibility that the observation is due to faulty measurement cannot be ruled out entirely. Being below the frontal zone, the deep maximum is not of direct concern here.

The nitrate profile of the B series casts (fig. 29) shows that only at the cool station were there considerable changes at depth. The information available does not provide any obvious explanation of these changes, and the low value at 125 m. may be erroneous. The marked gradient between about 40 and 50 m. on the cool side corresponds fairly well with those of temperature, thermosteric anomaly, and oxygen (figs. 17, 21, and 26). Below 40 m. on the cool side the oxygen content decreases rapidly as the nitrate increases rapidly; however, the relation is not so clear-cut on the warm side.

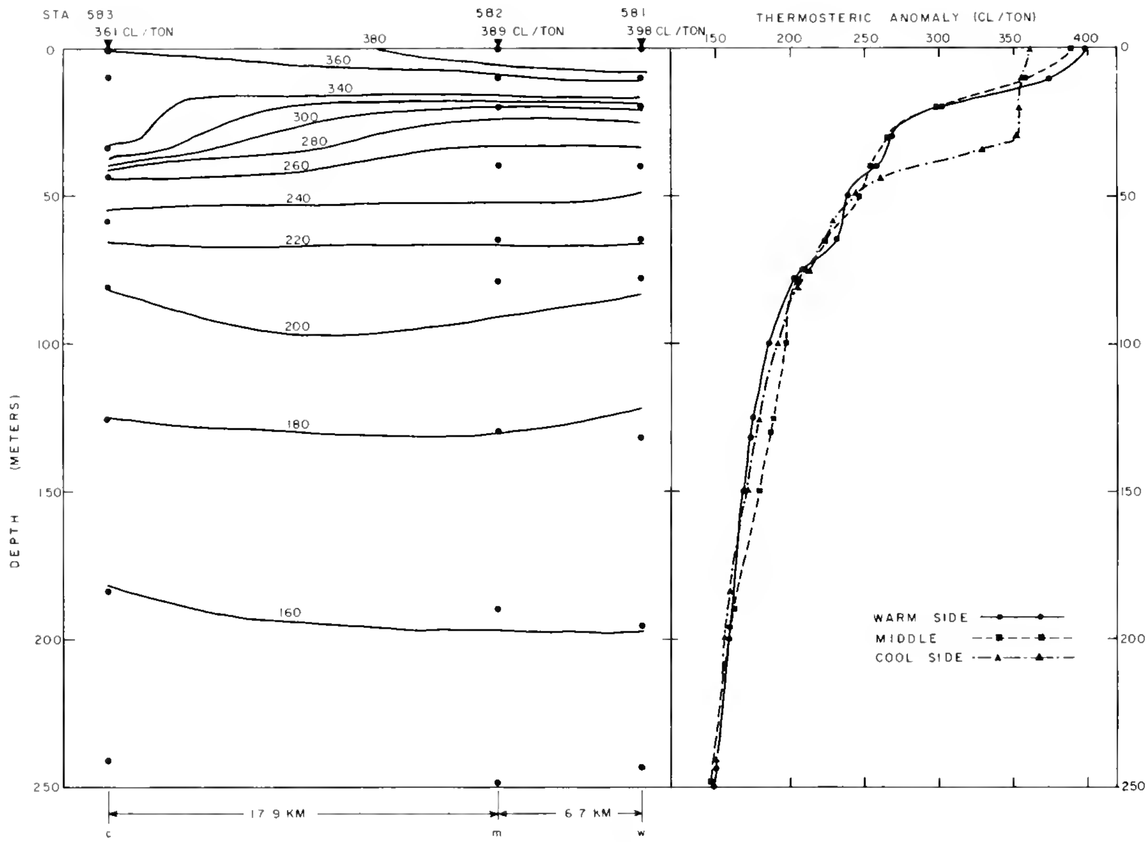

Figure 21.--Thermosteric anomaly (δ_T) profile and δ_T-depth curves for the first triplet (B) of hydrocasts at front 5 (22 April 1961). c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

The nitrate profile of the E series (fig. 29) shows no marked features in the upper waters, but nitrate concentration in the middle is less than on either side below 30 m. Oxygen isopleths, on the other hand, generally are deeper in the middle below 30 m. (fig. 27), indicating the relationship between the oxygen and nitrate concentration. Oxygen is used in the oxidative decay of dead matter, which accounts for the relationship observed.

Chlorophyll a distribution.--The amount of phytoplankton is estimated by the chlorophyll a content of the water. Figure 30 shows the profile of chlorophyll a determined from the data of a triplet of Van Dorn plastic sampler casts at the time of the B series of hydrocasts. The profile maximum (>0.6 mg. chl. a m.$^{-3}$) occurs at about 25 m. at the "middle" station. The station maxima correspond roughly to the pycnocline (fig. 21). The depths of the station maxima correspond to relatively high values of dissolved oxygen but there is no obvious correlation between chlorophyll a and dissolved oxygen. Although the location of the profile maximum in the middle suggests that phytoplankton has been aggregated by (or produced at) the front, it should be borne in mind that the samples were at only four depths: surface, 25, 40, and 100 m. Maxima as great as that found at 25 m. in the middle may actually have existed to either side but at depths not sampled. The reasons for sampling at only four depths per cast were (1) to obviate a marked time lapse between samplings during which the front might shift, and (2) to free the water filters of earlier samples in time for later ones.

Productivity.--The great importance of minimizing the difference in starting times of productivity experiments confined our observations of productivity to the surface water. Incubation of samples should start as close to local apparent noon as possible. It took at least half an hour to cross the front (at 9 knots); hence the unavoidably few observations.

Surface productivity increased on passing from the warm side to the cool; the values were 6.87, 11.88, and 16.38 mg. C/m.^{2}/day. These observations were made a day later than those of chlorophyll a.

Zooplankton and micronekton distribution.--In the introduction I stated that there is a widely held opinion that a front (a convergent

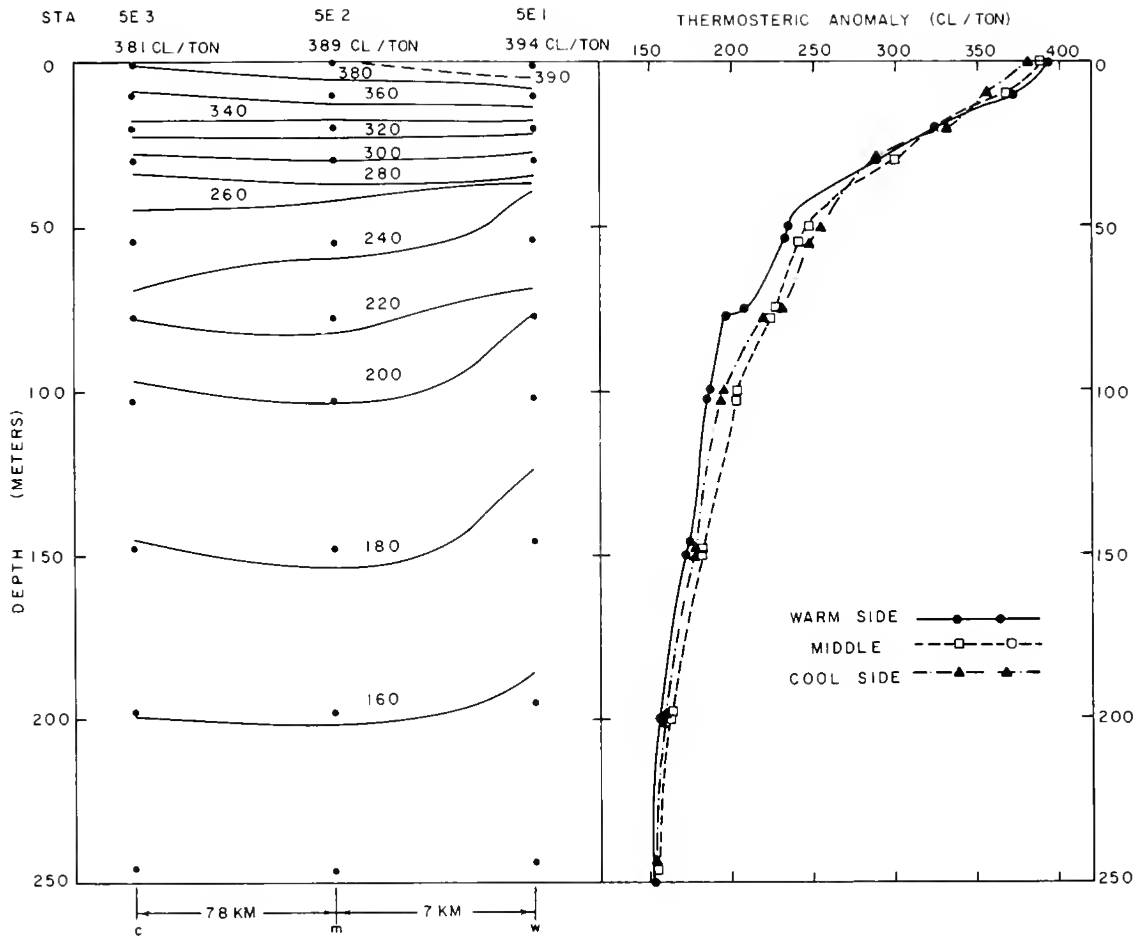

Figure 22.--Thermosteric anomaly (δ_T) profile and δ_T-depth curves for the second triplet (E) of hydrocasts at front 5 (23 April 1961). c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

one, at any rate) accumulates plankton, either mechanically or by providing favorable conditions for its increase. This opinion is backed by only a few direct observations (Uda, 1938; Knauss, 1957; King and Hida, 1957, and others).

There was not enough time to make a thorough study of the plankton distribution at front 5, and our results do not all confirm the aggregation hypothesis. We made three kinds of tow to sample zooplankton: (1) oblique hauls to a depth of about 300 m., except two inshore; (2) horizontal hauls near the surface, both kinds being made with a nonclosing net of 1 m. mouth diameter; and (3) horizontal hauls, above, in, and below the thermocline, simultaneously, with Clarke-Bumpus (C-B) closing nets of 25.4 cm. mouth diameter. One kind of tow was used to sample micronekton: an oblique haul to about 100 m. depth with a 1.52- by 1.52-m. square-mouthed net. Micronekton consists of small organisms longer or wider (disregarding antennae, etc.) than 5 cm., but less than 15 cm.; both these limits are arbitrary. Only fish present any difficulty in this assignment, and they, not often.

We made all hauls as nearly as possible along an isotherm (warm, middle, or cool). The isotherm desired was noted from the thermograph, and the ship was stopped and allowed to drift. It usually drifted along an isotherm, and its direction of drift was used for the tow. We checked the thermograph during the tow to ensure that the haul did not pass into water of undesired surface temperature while the ship steamed.

Table 2 summarizes the results of zooplankton and nekton net hauls. I have standardized catches to volume (ml.) per 1,000 m.^{3} (10^3m.^{3}) of water strained. This standardization is based on data from a flowmeter mounted in the mouth of the zooplankton nets, but is empirical for nekton net tows, being based on a filtration coefficient of the 1.52- by 1.52-m./net, on distance, and on duration of the tow (Blackburn and associates, 1962). The two main components of the catches are separated

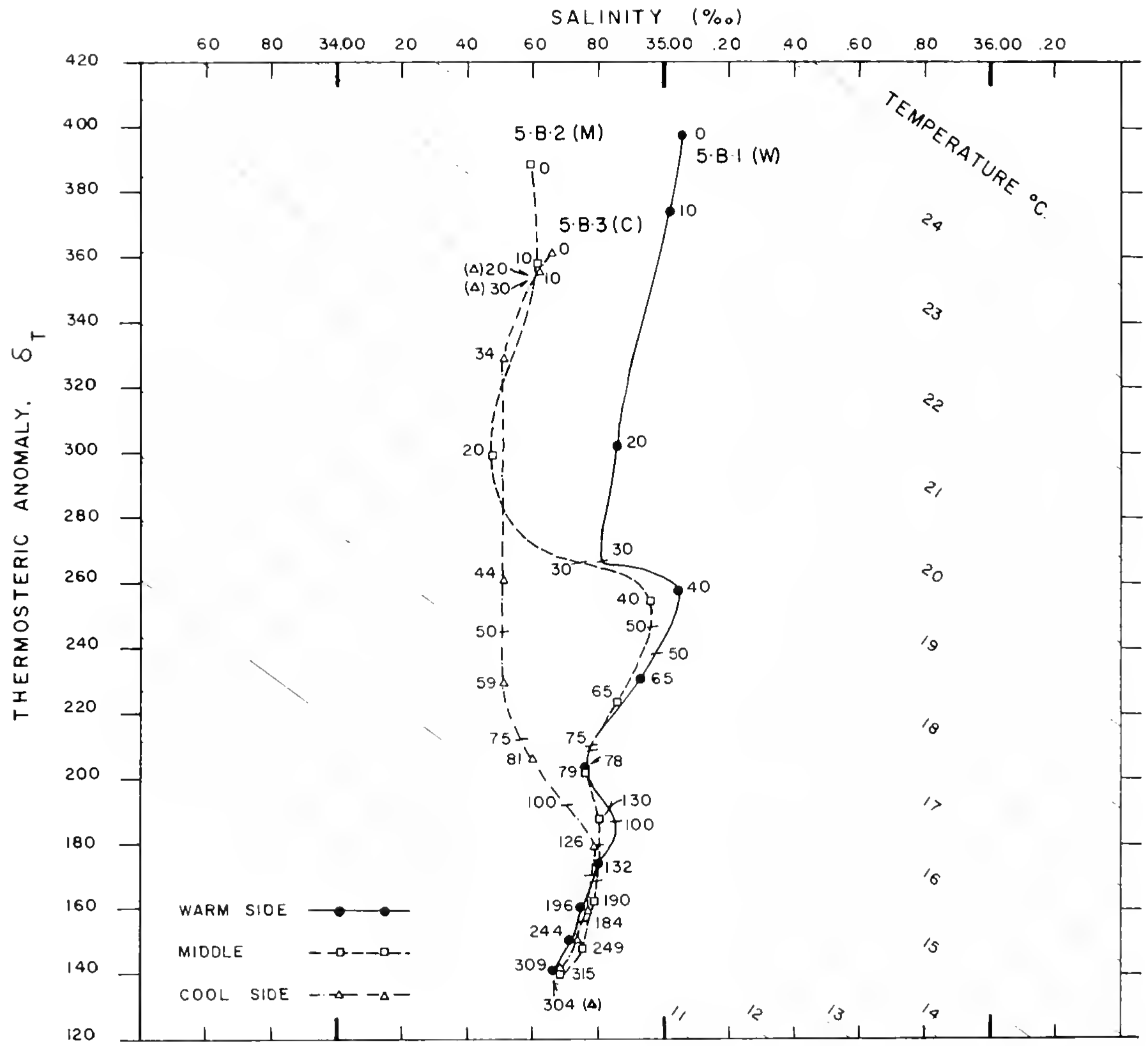

Figure 23.--T-S curves (on δ_T field) for the three B-series hydrocasts. Numbers against curves indicate depths.

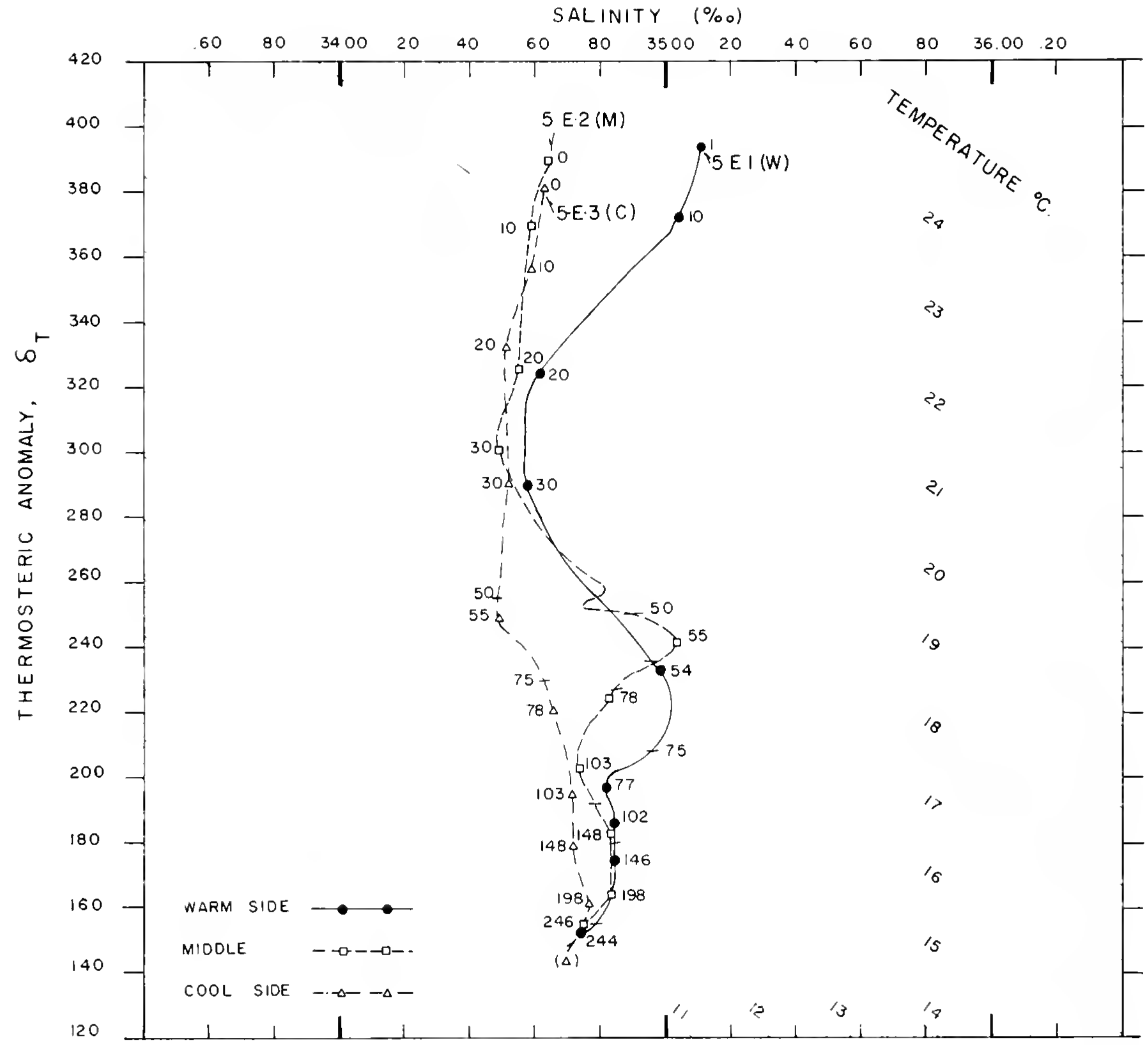

Figure 24.--T-S curves (on δ_T field) for the three E-series hydrocasts. Numbers against curves indicate depths.

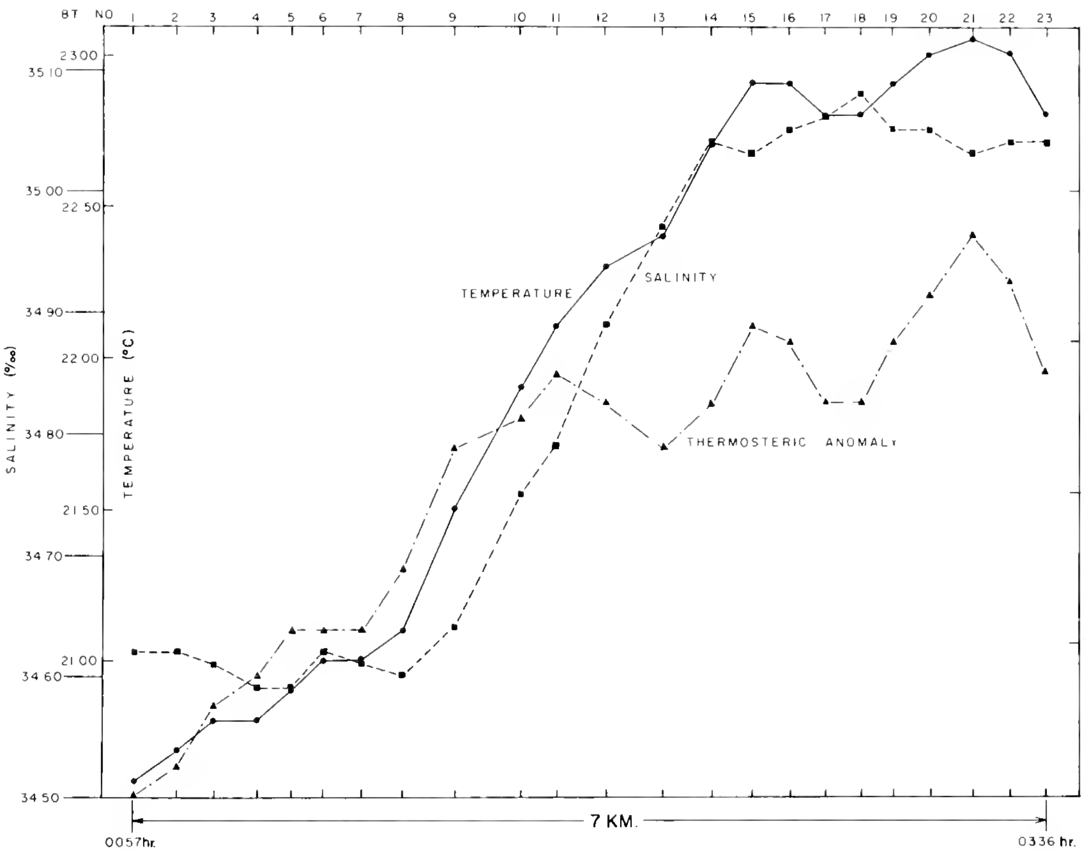

Figure 25.--Temperature, salinity, and thermosteric anomaly distribution across front 5 at the surface, as determined on BT pass no. 3 (21 April 1961). See fig. 15 for corresponding vertical temperature distribution.

in table 2, because I assume that zooplankton could be aggregated by the front, whereas the micronekton could not, though it might be attracted to the front by the plankton.

To determine whether the front was a focus of organisms, ratios of standardized volumes from one haul to the next across the front have been given in table 2 (value for the warm side set at unity). If the front aggregates plankton, the volume in the middle should greatly exceed that on either side. Significance of differences has been taken as half or double a given value, based on studies by Winsor and Walford (1936), Winsor and Clarke (1940), and Silliman (1946), although their studies were of variability in counts, not volumes. The present author (unpublished)[4] has obtained comparable results for volumes of crustacean zooplankton, though for salps the confidence limits are much wider.

The sampling methods are standard and, with respect to front studies, are open to criticism for the following reasons:

(1) The oblique hauls sample water well below the frontal zone (i.e., deeper than 120 m.). I believe, however, that contributions from below the frontal zone are (1) relatively independent of the front and not greater on one side than on the other; and (2) relatively small, because one set of hauls was taken at night when effects due to vertical migration would be minimal, and the other set was taken at dusk when these effects would be tending to a minimum (i.e., plankton mostly in upper 100 m.).

(2) Oblique hauls on either side of the front may sample parcels of water from the opposite side, by virtue of the Z-shaped interface (figs. 15, 19, and 20). This event is possible (see cast profiles, figs. 19 and 20), but the data show that the cool side has a higher standing crop than the warm side; such differences would tend to dissappear if the haul on the warm side were sampling a significant amount of the cool water, or vice versa.

We may suppose, then, that the catches of the oblique hauls reflect fairly well the effect of the front on the biota. Judging from the results of the two sets of oblique hauls (A and F series), zooplankters are concentrated in the front (table 2).

A similar conclusion might be drawn from the results of the Clarke-Bumpus net tows (5C1 - 3) above the thermocline, but these

[4] Griffiths, R. C. "The variability of volumes of zooplankton taken in oblique, paired, one-meter net hauls."

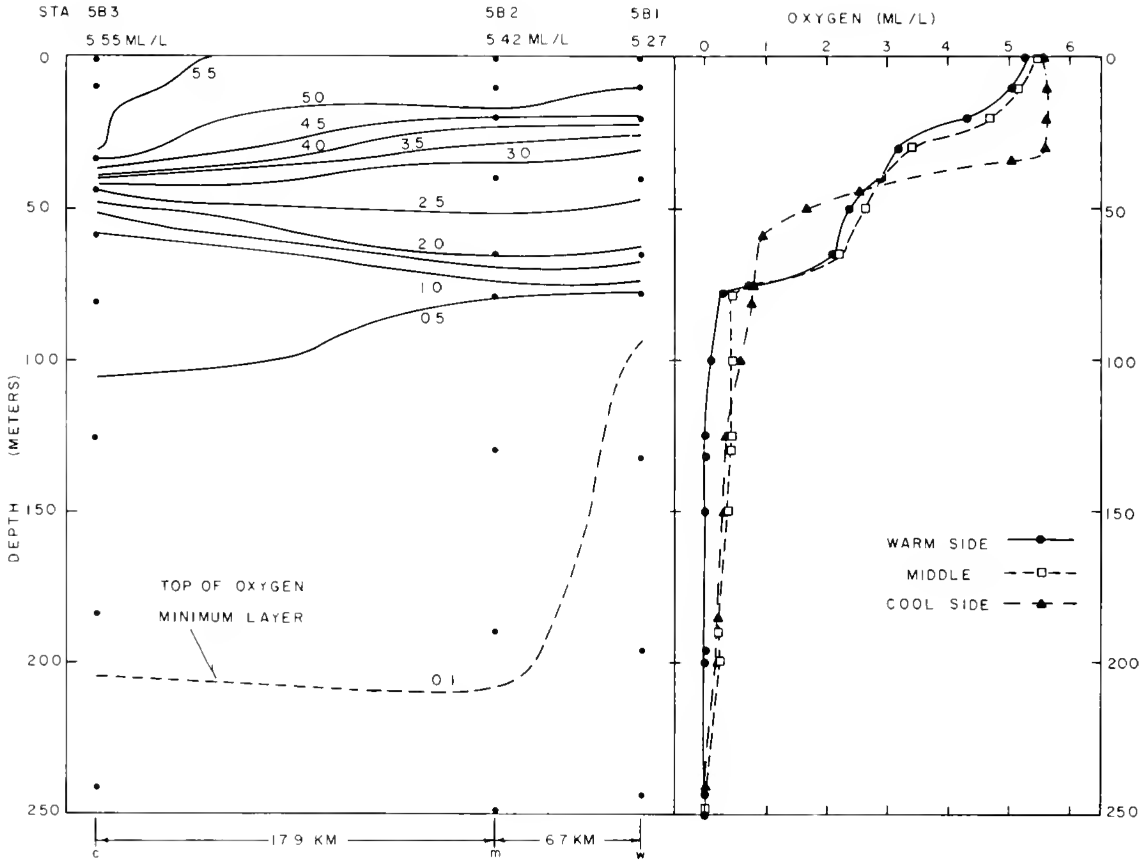

Figure 26.--Oxygen profile and oxygen-depth curves for the first (B) triplet of hydrocasts at front 5 (22 April 1961). The dashed contour (0.1 ml.l.$^{-1}$) arbitrarily marks the upper boundary of the extensive oxygen minimum typical of the eastern tropical Pacific water. c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

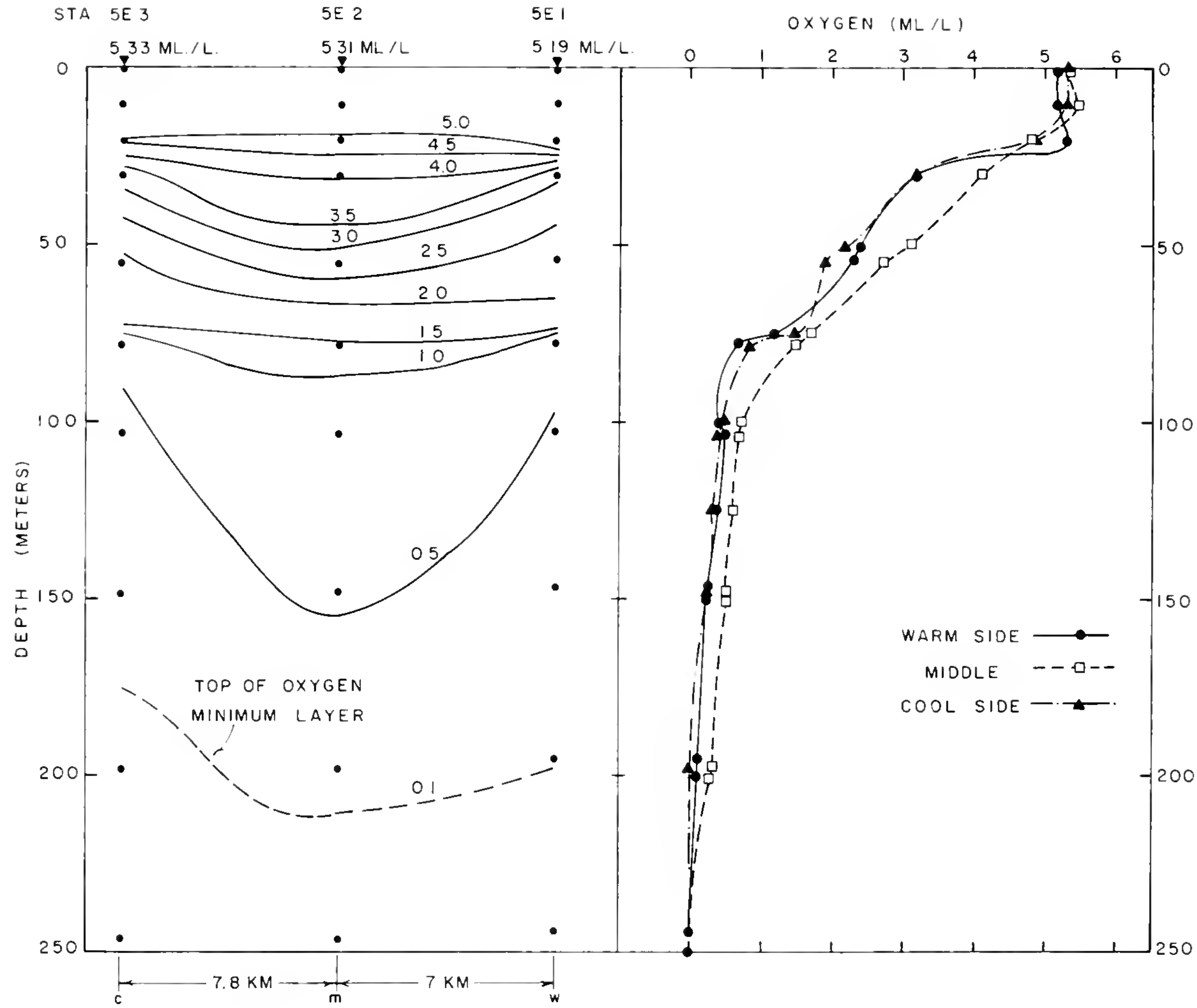

Figure 27.--Oxygen profile and oxygen-depth curves for the second (E) triplet of hydrocasts at front 5 (23 April 1961). c = cool side; m = middle; w = warm side; • = Nansen bottle depths in profile.

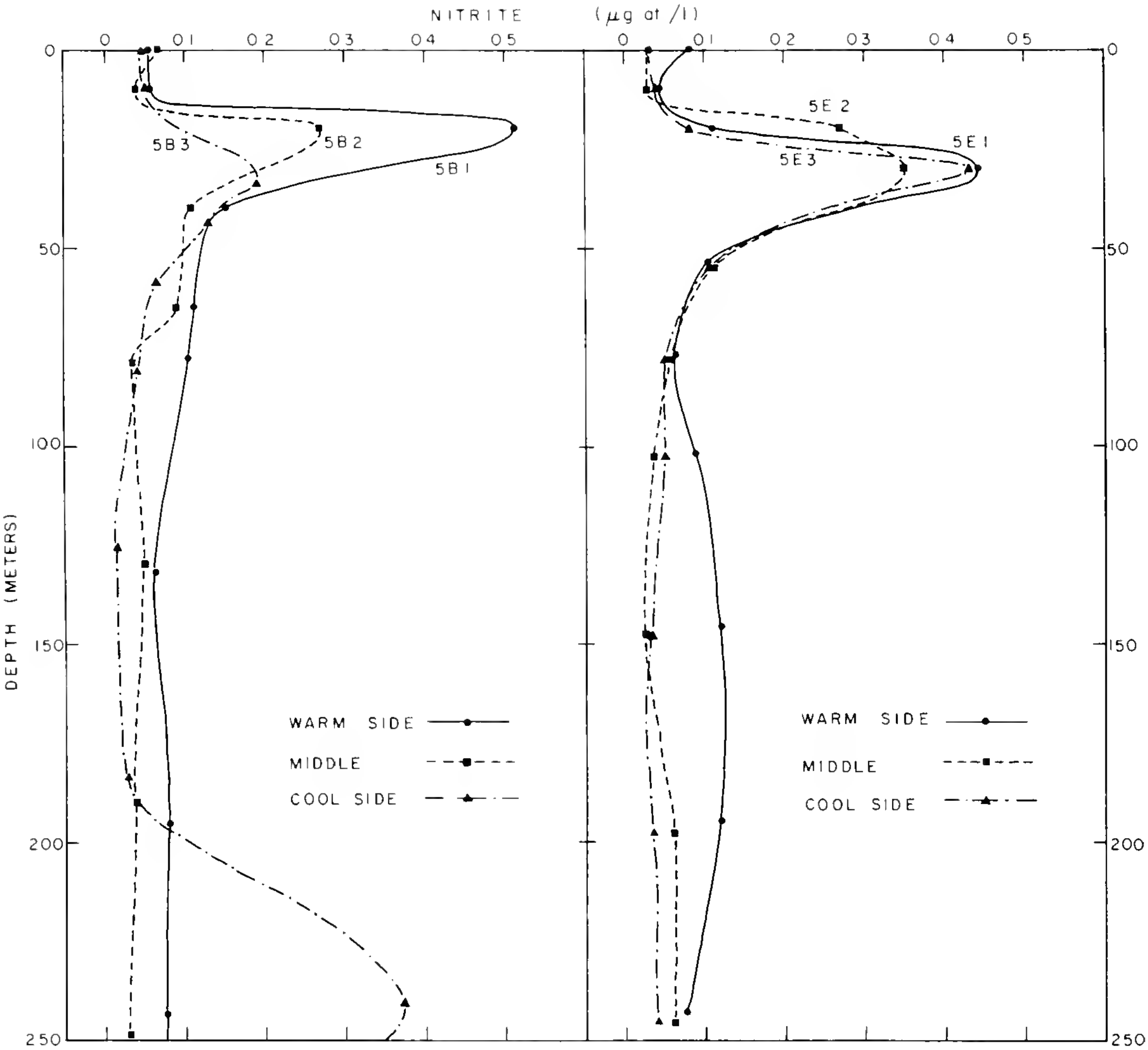

Figure 28.--Nitrite-depth curves for the two triplets of hydrocasts made at front 5. B series in left panel; E series in right.

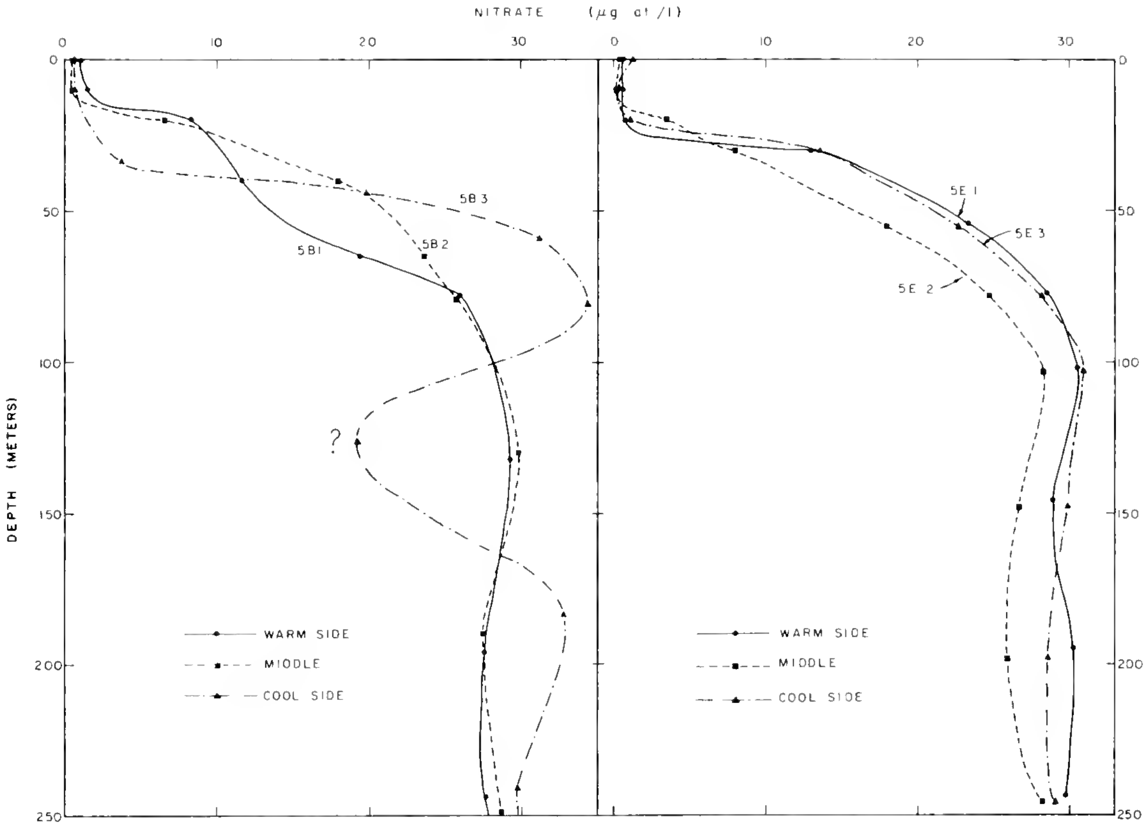

Figure 29.--Nitrate-depth curves for the two triplets of hydrocasts made at front 5. B series in left panel; E series in right.

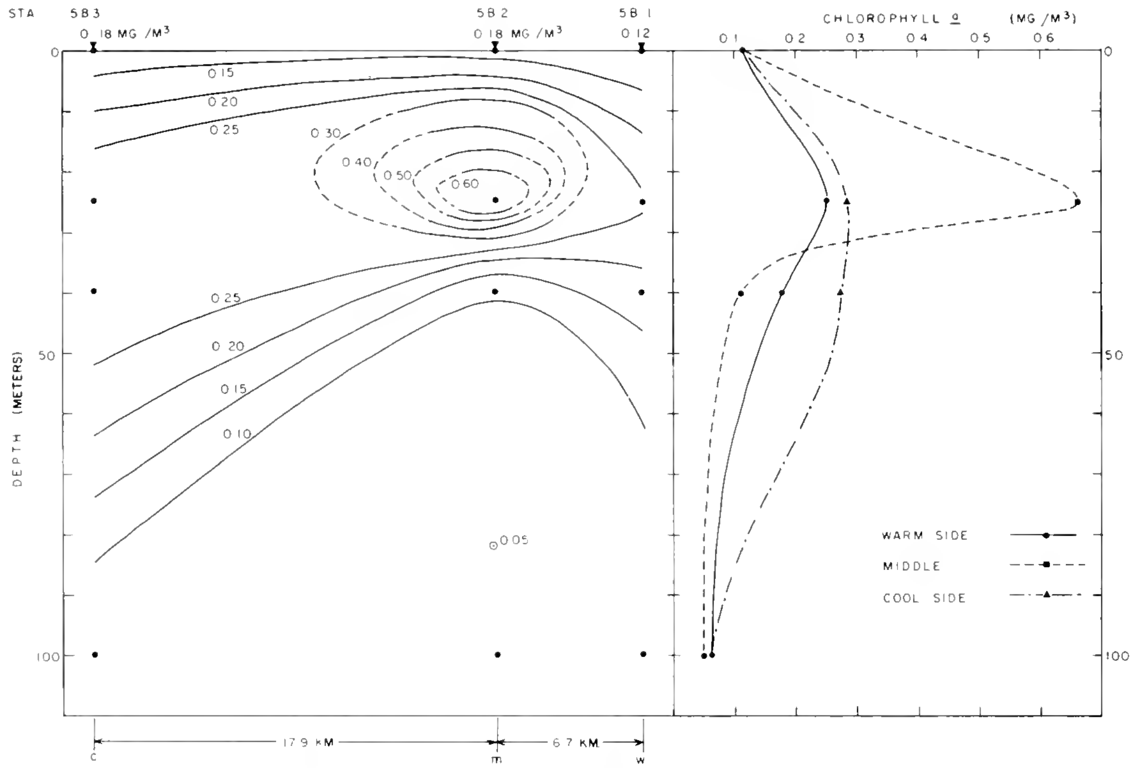

Figure 30.--Chlorophyll a profile and chlorophyll a-depth curves for a triplet of observations that closely corresponded in position to the first (B) triplet of hydrocasts at front 5. Dashed-line contours in the profile are somewhat speculative. c = cool side; m = middle; w = warm side; • = Van Dorn Sampler depths in profile; units are mg./m.^{3}

nets sampled so little water (~70 m.^{3}) per tow that the differences probably are not reliable. The C-B samplers in the thermocline caught increasing amounts from the warm side to the cool. These C-B samplers were towed at three depths at one time on one wire; the one below the thermocline failed in each haul.

The horizontal surface hauls show increasing volume towards the cool side, the ratios (1.0:3.4:8.7) being significantly different. This trend resembles that obtained using C-B samplers in the thermocline and that shown by surface productivity determinations. Each of the horizontal surface hauls immediately followed a nekton-net haul.

I presume that micronekton are strong swimmers and therefore are not mechanically aggregated by the front. The zooplankton component (mostly large euphausiids, about 3 cm. long) of the nekton net hauls was much more abundant in the middle and on the cool side than on the warm side. The large euphausiids were not caught by any nets other than the 1.52- by 1.52-m. nekton net, which samples to a maximum depth of 115 m. (Blackburn and associates, 1962).

Aliquots of each sample were sorted, and the numbers of the predominant groups (e.g., copepods) were counted. The volumes of the most abundant of these were measured by the method of Yentsch and Hebard (1957). Table 3 shows the ratios of counts standardized to the full sample and to 10^3m.^{3} of water strained. These ratios, by groups, can be qualitatively compared with those given, by sample volume, in table 2. Again, the value for the warm side is set at unity.

Some of the ratios in table 3 are particularly interesting and are summarized in table 4. Besides these are the relatively high euphausiid catches in the middle and on the cool side by the nekton net, as mentioned above. Pteropods, which were very abundant in the middle according to the results of the A series oblique tows, also were very abundant in the catch on the cool side by the F series oblique tow, but were absent from the hauls in the same (F) series in the middle and on the warm side. Much more sampling is needed to elucidate precisely the effects of the front on animals.

A factor that cannot be assessed is grazing of the zooplankton by the micronekton. The average grazing rate, for example, might be less in the middle than it is on either side. If it were, it could perhaps explain the relatively greater amounts of copepods and euphausiids in

Table 2.--Results of net hauls made at the Cape San Lucas Front (front 5)

Station	Time of day	Depth of tow (m.)	Volume plankton ml. per $10^3 m.^3$	Ratio of volumes	Volume micronekton ml. per $10^3 m.^3$	Ratio of volumes	Dominant forms (by volume or number)	
							Zooplankton	Micronekton[3]
				OBLIQUE 1-m. NET HAULS				
5A1 (w)[1]	n[2]	300	20	1	95	1	copepods, chaetognaths, ostracods	red crabs
5A2 (m)[1]	n	261	101	5.0	3	0.03	copepods, euphausiids, pteropods	
5A3 (c)[1]	n	329	43	2.2	158	1.7	copepods, pteropods, euphausiids, ostracods	red crabs
5F1 (w)	d[2]	200	20	1	120	1	copepods, chaetognaths	red crabs
5F2 (m)	d	170	199	10.2	1,638	13.7	euphausiids, copepods	red crabs
5F3 (c)	d	321	75	3.8	12	0.1	copepods, chaetognaths, pteropods, siphonophores	red crabs
				HORIZONTAL 1-m. NET HAULS				
5D2 (w)[1]	n[2]	3	52	1	46	1	copepods, chaetognaths, pteropods	a large salp
5D3 (m)[1]	n	3	179	3.4	0	--	chaetognaths, copepods, pteropods, siphonopheres	
5D1 (c)[1]	n	3	452	8.7	52	1.1	copepods, pteropods, siphonophores	salps
				HORIZONTAL CLARKE-BUMPUS NET HAULS				
				i) ABOVE the thermocline				
5C1 (w)	d[2]	15	7	1	0	--	copepods, chaetognaths, pteropods	
5C2 (m)	d	20	78	11.1	0	--	chaetognaths, copepods	
5C3 (c)	d	15	58	8.3	0	--	euphausiids, copepods, siphonophores	

Table 2.--Results of net hauls made at the Cape San Lucas Front (front 5)--Continued

Station	Time of day	Depth of tow (m.)	Volume plankton ml. per 10^3m.[3]	Ratio of volumes	Volume micronekton ml. per 10^3m.[3]	Ratio of volumes	Dominant forms (by volume or number)	
							Zooplankton	Micronekton[3]
HORIZONTAL CLARKE-BUMPUS NET HAULS (con.) ii) IN the thermocline								
5C1 (w)[1]	d[2]	40	59	1	0	--	red crab larvae, chaetognaths, copepods	
5C2 (m)[1]	d	35	63	1.1	0	--	euphausiids, red crab larvae, copepods	
5C3 (c)[1]	d	25	127	2.2	0	--	euphausiids, copepods, chaetognaths	
OBLIQUE 5-ft. NEKTON NET HAULS								
5D2 (w)	n[2]	100	0.1	1	66	1		red crabs, fish, prawns
5D3 (m)	n	100	5	50	9	0.14[4]	euphausiids	red crabs, fish
5D1 (c)	n	100	5	50	8	0.12[4]	euphausiids, stomatopod larvae	fish

[1] w = warm side; m = middle ; c = cool side of front. [2] n = night; d = dusk.
[3] Micronekton is, roughly speaking, a small organism of minimum linear dimension 5 cm. and of maximum linear dimension of, say, 15 cm.
[4] Excludes zooplankton component; see footnote to table 3.

the middle according to the F series of oblique hauls than the corresponding amounts according to the A series of oblique tows made on the previous night (see tables 3 and 4, and text below). The chaetognaths in these same hauls seem to have accumulated even more rapidly than the copepods and euphausiids in the lapse between the A series of hauls and the F series.

The following table summarizes the points just mentioned.

Organisms:	(A series) (w)	(m)	(c)	Oblique tows	(F series) (w)	(m)	(c)
Copepods	1.0	1.7	0.8		1.0	5.6	2.2
Euphausiids ...	1.0	7.9	4.0		1.0	11.0	2.5
Chaetognaths ..	1.0	0.5	0.4		1.0	4.5	2.6

This marked accumulation may also have happened to the chaetognaths and copepods in the surface waters (compare results of surface tows with those of the C-B tows above the thermocline, in table 3, bearing in mind the real limitations of the results obtained by C-B samplers).

Disregarding the plankton component of the 1.52- by 1.52-m. net hauls, the abundance of micronekton in the middle of the front is, on the average, about the same as that on the warm side and about half as great as that on the cool side (on the average, the cool side has the most zooplankton). This information is derived from table 3 by omitting the euphausiid and stomatopod entries in the nekton data and recalculating the average values; whereupon the values 1.0:11.2:12.1 become 1.0:0.9:1.7.

There are two possible causes of the various relative abundances of component groups in the front, apart from effects of mechanical aggregation and predation: (1) in situ production of some groups is higher than for some others in different parts of the frontal system, and (2) some forms experience a relatively higher death rate than others when confronted with

Table 3.--Ratios of major groups of organisms in the net hauls made on the warm side, in the middle, and on the cool side of the Cape San Lucas Front (front 5). The ratios are of the counts, and the count of the warm side is set at unity. Ratios are given only when a group was represented in all catches of a triplet (one exception*)

OBLIQUE HAULS (1 METER NETS)

Organisms	Station 5A1 (w)	5A2 (m)	5A3 (c)
Copepods	1.0	1.7	0.8
Euphausiids	1.0	7.9	4.0
Pteropods	1.0	24.7	11.6
Ostracods	1.0	1.2	0.9
Chaetognaths	1.0	0.5	0.4
Average	1.0	7.2	3.5
Total plankton volumes from table 2, col. 5	1.0	5.0	2.2

Organisms	Station 5F1 (w)	5F2 (m)	5F3 (c)
Copepods	1.0	5.6	2.2
Euphausiids	1.0	11.0	2.5
Pteropods	--	--	--
Ostracods	--	--	--
Chaetognaths	1.0	4.5	2.6
Average	1.0	7.2	2.4
Total plankton volumes from table 2, col. 5	1.0	10.2	3.8

HORIZONTAL HAULS

i) SURFACE - 1-METER NET

Organisms	Station 5D2 (w)	5D3 (m)	5D1 (c)
Copepods	1.0	1.4	6.1
Euphausiids	1.0	2.1	5.2
Pteropods	1.0	3.2	27.0
Chaetognaths	1.0	1.8	1.6
Siphonophores	1.0	2.1	4.9
Average	1.0	2.1	9.0
Total plankton volumes from table 2, col. 5	1.0	3.4	8.7

ii) ABOVE THERMOCLINE - CLARKE-BUMPUS NET

Organisms	Station 5C1 (w)	5C2 (m)	5C3 (c)
Copepods	1.0	6.0	1.2
Euphausiids	--	--	--
Pteropods	--	--	--
Chaetognaths	1.0	14.0	1.1
Siphonophores	--	--	--
Average	1.0	10.0	1.1
Total plankton volumes from table 2, col. 5	1.0	11.1	8.3

iii) IN THERMOCLINE - CLARKE-BUMPUS NET

Organisms	Station 5C1 (w)	5C2 (m)	5C3 (c)
Copepods	1.0	0.8	1.8
Red crab larvae	1.0	0.5	--
Chaetognaths	1.0	0.1	0.8
Average	1.0	0.5	0.9
Total plankton volumes from table 2, col. 5	1.0	1.1	2.2

OBLIQUE HAULS--NEKTON NET

Organisms	Station 5D2 (w)	5D3 (m)	5D1 (c)
Red crab adults	1.0	0.04	--
Shrimps	1.0	.08	--*
Fish	1.0	.3	4.0
Leptocephalus	1.0	1.2	1.8
Squid	1.0	3.0	2.7
Euphausiids (plankton)	1.0	73.2	64.8
Stomatopod larvae (plankton)	1.0	.8	11.3
Average	1.0	11.2	12.1
Total volumes from table 2, col. 7[2]	1.0	.2	[1] .2

[1] Includes zooplankton. [2] See footnote 1 above, and 4 in table 2.

Table 4.--Ratios given in table 3 that indicate probable effects of the front on the distribution of animals

Type of ratio	Group of organisms	Type of net haul
High value on warm side as compared with middle and cool side	Red crab larvae............	C-B (in thermocline)
	Red crab adults............	1.52- by 1.52-m. nekton net
	Pandalid shrimps...........	1.52- by 1.52-m. nekton net
	Chaetognaths (marginal)....	Oblique tows, A series
High value in middle as compared with either side	Euphausiids................	Oblique tows, A and F series
	Pteropods..................	Oblique tows, A series
	Copepods, Chaetognaths	Oblique tows, F series and C-B (above thermocline)
High value on cool side as compared with middle and warm side	Stomatopod larvae..........	1.52- by 1.52-m. nekton net
	Pteropods, Copepods, Euphausiids, Siphonophores	Horizontal surface tows
Low values in middle as compared with either side	Chaetognaths...............	C-B (in thermocline)
	Fish.......................	1.52- by 1.52-m. nekton net

the strong environmental gradients that constitute the front (assuming all forms are equally aggregated).

On the whole, the cool side contributes more to the total plankton of the area than does the warm side,[5] though a marked maximum of a plankton component in the middle is commonly found. The outstanding exception to this is in the results of the surface net tows (if we ignore the chaetognath component), which strongly reflect the greater contribution of the cooler side. There may be an explanation for this: although they are marked, the horizontal property gradients at the surface are weaker than the vertical property gradients at greater depths (e.g., 30-60 m.); in other words, the effect of the front may be much less marked at the surface than at depth.

This explanation is not borne out by the results of the C-B tows which, however unfavorably C-B samplers may compare with other nets, can be compared satisfactorily with each other. Catches above the thermocline show marked aggregation in the middle (especially of copepods and chaetognaths); those in the thermocline show a much more general distribution of zooplankton.

To sum up: the data do not allow specific statements about the effect of the front on the biota, though they do support the aggregation hypothesis. Although, on the whole, micronekton does not congregate in the middle of the front, some of the results (see table 3, F series of oblique tows, red-crab component) suggest that it might do so occasionally.

Miscellaneous observations.--Incidental to all the special observations, we observed the general abundance of sea life, as well as sea and weather conditions. The sea was calmer north of a line bearing about 100° - 280° from Cape Falso than to the south of it; as the vessel went south the sea became steadily and quickly choppier, and the wind increased. This change was not great, however, and was the result of moving from the shelter of the land into the prevailing northwest wind, and was only partially related to the front itself. Marlin were particularly abundant here, and several sport-fishing boats caught marlin frequently in the calm water. Some turtles were observed, though turtles were more abundant further south; we saw them on the passage from Tres Marias Islands to Cape San Lucas. Sea birds were not abundant. We saw no tuna boats or schools of tuna during the period of study, but often took black skipjack on jigs at this front, and tuna boats were active and successful in the general area at that time (Griffiths, 1963).

The weather and sea conditions changed relatively little during the period of study except as noted; cloud cover and haze prevented star sights and often made it difficult to get good bearings.

The calm weather and the front's stability made observation of the front easy. This is in contrast to the fronts studied on cruise TO-60-1, except front 3; observations on these fronts are presented below.

[5] Integration of the chlorophyll a depth curves in figure 30 shows that probably there is most chlorophyll a on the cool side too.

Front 1

Front 1 (fig. 1) was found by thermograph early in the morning on 7 May 1960. As with the other fronts studied, there was no obvious demarcation in the ocean surface, though differences between the waters of either side could be seen. We started the thermograph survey as a regular pattern, a "rectangular spiral", but this we modified (at 0913 hours) as temperature data were gathered (fig. 31). No front was crossed between 0913 and 0935 hours, nor after turning 90° to the right. At 0935 the vessel reversed its course and immediately passed through the front. To avoid confusion this backtrack is set off from the first track (0928 - 0935 hours) in figure 31. This experience demonstrates the sort of difficulty that can be expected in the study of fronts, particularly of the faster moving and more sinuous kind.

The surface currents as measured by GEK are shown on figure 31; flow was slightly faster on the cool side.

The track between 1259 and 1345 hours was in water of about 19.5° C. This isotherm was in the front earlier in the day. Assuming that this is a suitable indicator isotherm and that the drawn track is not markedly in error, we may conclude that the front moved about 2 to 3 miles in 4 to 5 hours - an average speed of about half a knot.

On turning left at 1345 hours, we expected to recross the front. Although the temperature increased slowly up to about 20° C., no front was encountered, so we returned to the regular station pattern of cruise TO-60-1.

The frontal isotherms at front 1 fall into two groups (fig. 31). These are not joined because there is evidence that the front apparently was moving roughly westward; hence, the front found between about 0800 and 0930 hours likely would have moved to a position approximately south of the front as found between about 1100 and 1300 hours. Therefore, to join the two groups of isotherms would introduce a false curvature. It is possible also that the orientation of the front may have changed during the day and that the southern part diffused.

Although the temperature distribution indicates a westward movement, the fact that 20° C. water was found (at about 1400 hours) <u>east</u> of 20.5° C. water (at about 0950 hours) contradicts this idea. A possible solution is that the front was sinuous; and, owing to accumulating navigational error, there can be some doubt of the accuracy of the plotted track later in the day in relation to one plotted earlier in the day.

The direction of flow according to the GEK observations is as would be expected from geostrophic flow calculations, assuming the surface temperature reflected the density structure over some depth of no motion. It is difficult to reconcile the northerly flow (as shown by GEK with the apparent westward movement indicated by the isotherm distribution in time (but see p. 16).

If a front is in motion, determining both its main orientation (axis) and its change of position is difficult. Even though the front as a whole may be stationary, parts of it may move sinuously. Front 1 exemplifies this problem, but the problem pertains also to fronts 2 and 4, and, to a much lesser degree, to fronts 3 and 5.

The temperatures at front 1 were such that when compared with the isotherms of the general area (fig. 2) there can be little doubt that the warmer water was regular surface water and the cooler water was upwelled water of the California Current system. Station 15, by front 1, was, in fact, at the southern end of a tongue of cool, upwelled water originating inshore well to the north of Cape San Lucas (fig. 2).

Front 2

At front 2 (fig. 32) we guided the ship so the movement of the front would be detected, though the general form would not. Presumably because of time-lag and sinuosity the movement of the front within the narrow area studied was not defined clearly.

Because no thermograph survey was attempted, BT passes (fig. 32) were started first. As at front 5, the temperature profiles drawn from the BT data were similar for all three passes; pass no. 2 is taken as representative (fig. 33).

The important characteristic is a thin layer of relatively warm (~20° C.) water spreading across the front between depths of about 35 and 60 m. In all three profiles, it weakens or disappears immediately beneath the front proper (i.e., where isotherms cut the sea surface). Presumably, the warm, thin layer on the cool side originated from water on the warm side. This warm layer could be derived from an intrusion below the surface of the water found at front 5 (fig. 15), such an intrusion being separated from its source by a complementary intrusion, above and perhaps below, of cool water, as might have happened eventually at front 5.

On pass no. 2, we took surface water samples with each BT and measured the salinity of each sample. The warm water was more saline, as at front 5. With contemporaneous measurements of surface temperature and salinity, we determined the corresponding thermosteric anomaly values. These three properties are plotted in figure 34 in relation to the BT pass. They have a strong qualitative and quantitative similarity to those of front 5 (fig. 21). The distributions, computed as before by dividing the maximum difference by the distance between the BT's corresponding to that difference, are temperature, 0.33° $C.km^{-1}$; salinity, 0.12 ‰ km^{-1}; and thermosteric anomaly 5.1 $cl.ton^{-1}km^{-1}$. The respective BT's are 3-14 (T), 7-14 (S),

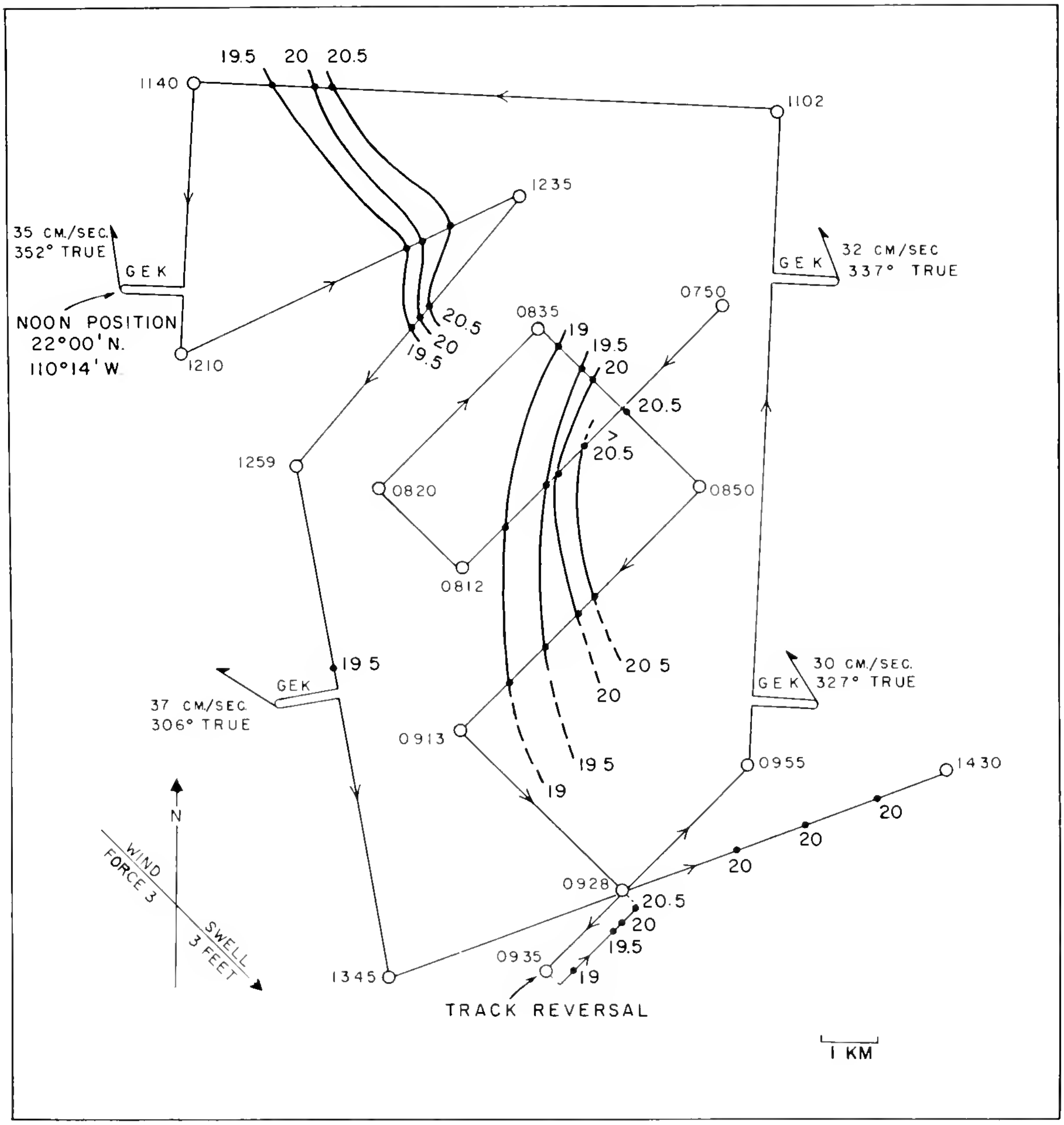

Figure 31.--Track of thermograph survey of front 1 (0750-1430 hours 7 May 1960), with surface isotherms superimposed. Results of four GEK observations also are shown. The track after course reversal (0935) has been displaced for clarity but closely corresponds to the track between 0928 and 0935 hours.

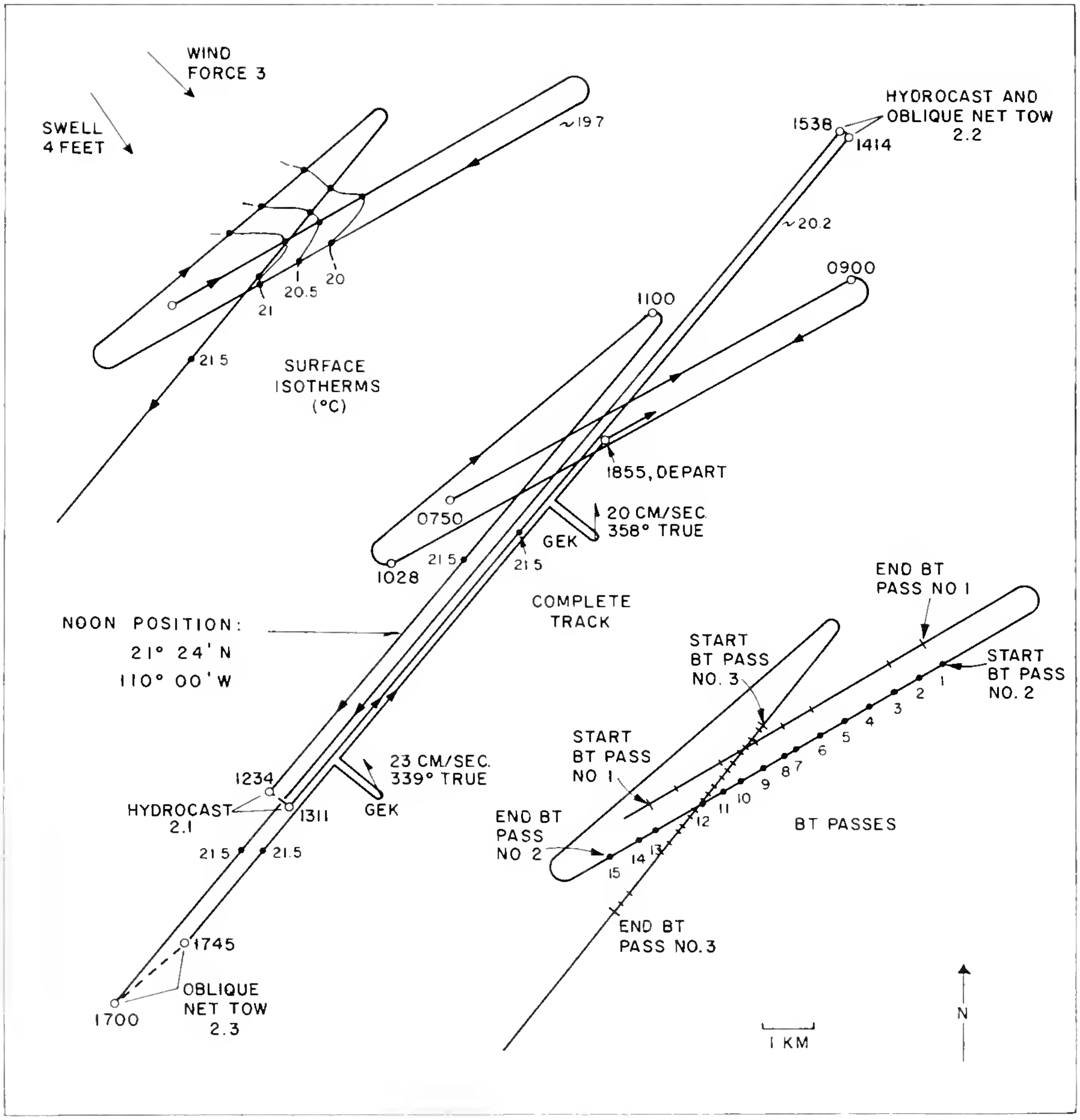

Figure 32.--Track at front 2 (10 May 1960), showing positions of hydrocasts, net tows and GEK observations. Isotherm contours (where practical to draw) and BT passes are shown separately offset.

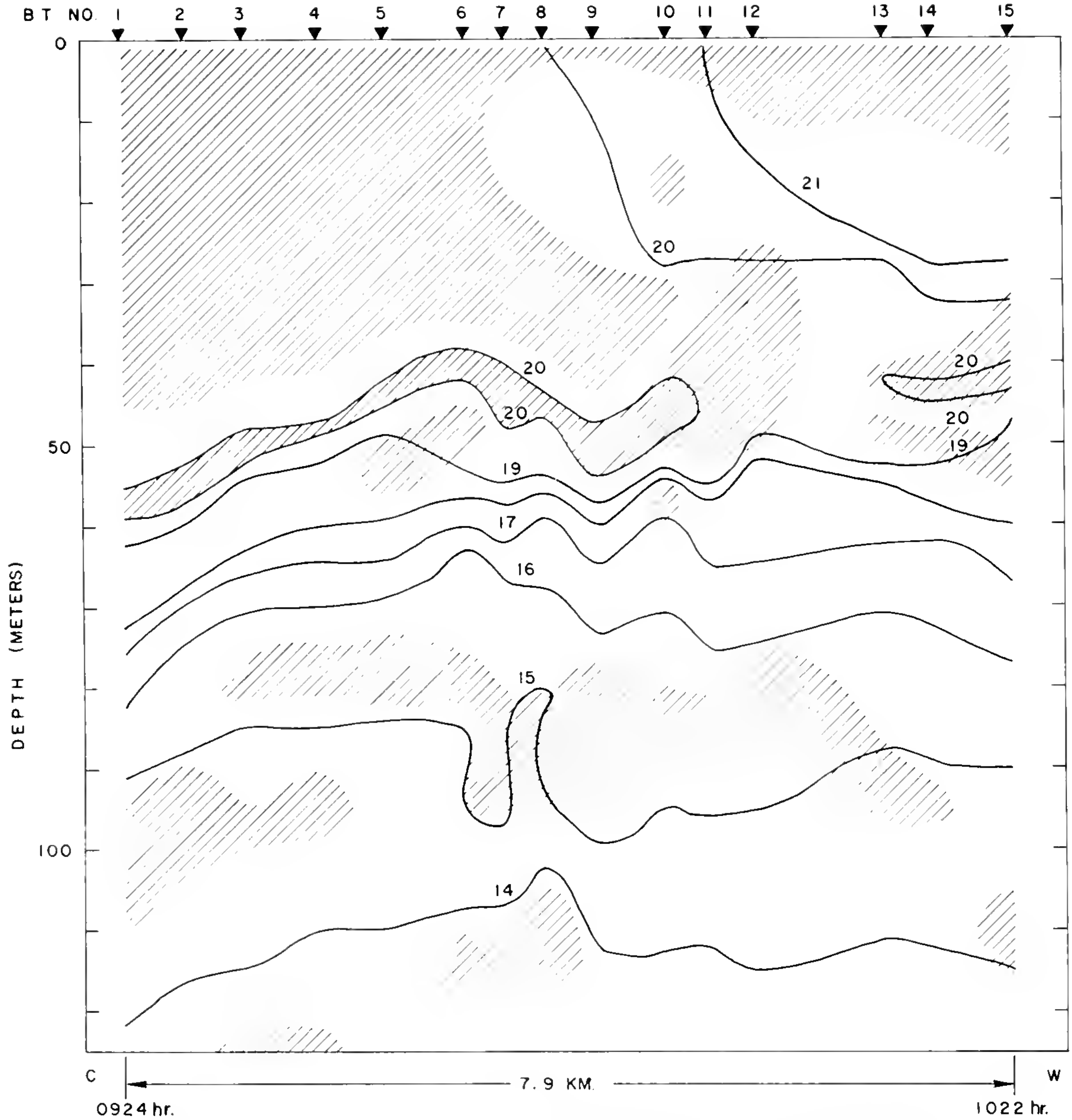

Figure 33.--The temperature profile from BT pass No. 2 across front 2 (10 May 1960). Cross-hatching shows water that is practically isothermal vertically.

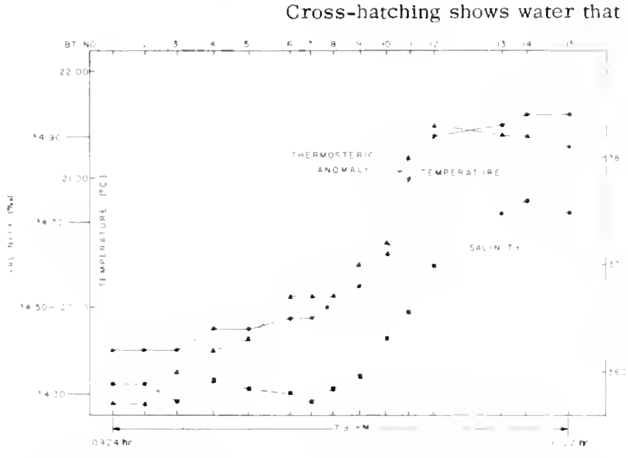

Figure 34.--Temperature, salinity, and the thermosteric anomaly distribution across front 2 at the surface, as determined on BT pass no. 2.

and 2-12 (δ_T). Note that where alternative choices are available (e.g., salinity value at BT 3 same as that at BT 7) I chose the value to maximize the gradient.

The two hydrocasts at front 2 (one on either side) were relatively far from the front, and any profiles derived from their data would not be highly meaningful. There was evidently a strong thermocline at about 60 m. Isotherms cutting the surface in the middle or on the cool side were deeper on the warm side. The salinity data from the hydrocasts suggest a complicated salinity structure, like that of front 5. The nature of this complication is partially shown by the T-S curves for the two hydrocasts (fig. 35). According to the T-S curve for the warm side, the water is fairly typical California Current water below about 50 m.

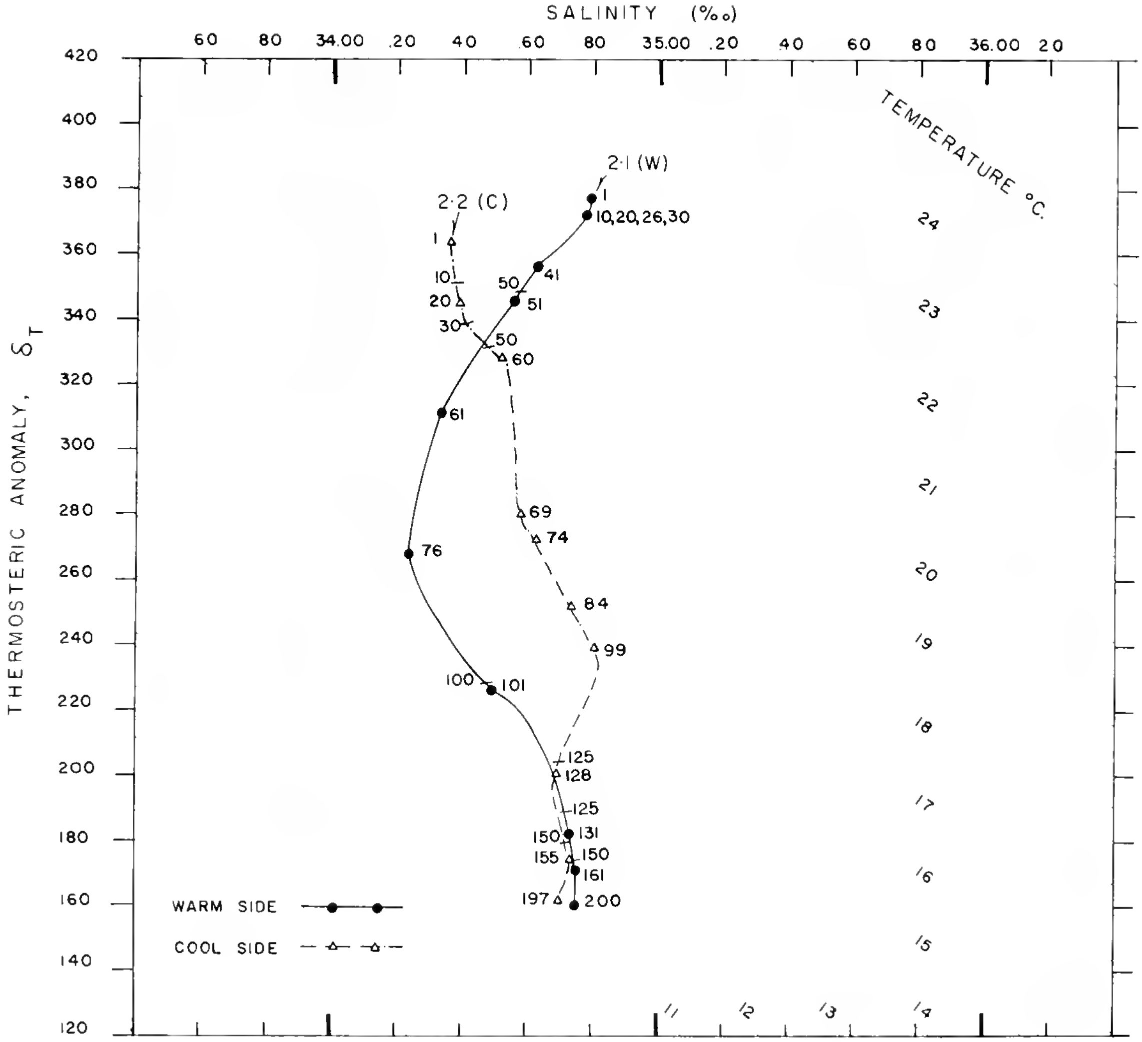

Figure 35.--T-S curves (on δ_T field) for the two hydrocasts (2.1 on warm (w) side, 2.2 on cool (c) side) at front 2. Numbers against curves indicate depths.

The water on the cool side has characteristics of California Current water (cool, with low salinity) at the surface, but its salinity rapidly increases with depth (unlike California Current water). The result is an altogether anomalous T-S curve, but below about 90 m. it conforms to either equatorial Pacific or Gulf water (figs. 7 and 8). There is a relatively small density difference between the two sides of this front at the surface (about 15 cl.ton^{-1}) but at depths down to about 70 m. the density differences are greater than those found at front 5 (p. 24).

There was a strong vertical gradient of dissolved oxygen and of phosphate (PO_4-P) at about 70 m. depth, agreeing more or less with the thermocline.

The catches of one oblique 1-m. net haul on either side of front 2 afford no information about the effect of this front on the zooplankton distribution. The compositions of the two catches differ markedly (table 5).

Front 4

This front was located very near the position of front 2 (fig. 1), but 13 days later. Because the temperatures on either side and the difference between them were similar to those at front 2, and because the two fronts were at the same place, it was expected that they would have similar properties, but in general they do not.

Among the common forms, chaetognaths (not significantly) and euphausiids are relatively more abundant on the cool side than on the warm; siphonophores (only the more or less solitary sea bells were found) are somewhat, but not significantly, less numerous on the cool side. Note the five exclusive groups

Table 5.--Summary of oblique 1-m. net hauls at fronts 2 and 4. Counts (from aliquots) have been standardized to full sample size and to $10^3 m.^3$ of water strained. w = warm side; c = cool side

Organisms	Station			
	2.3 (w)	2.2 (c)	4.3 (w)	4.4 (c)
Volume of catch in ml. per $10^3 m.^3$	35	120	89	79
Counts of organisms:				
Copepods	11,325	12,116	8,334	22,720
Chaetognaths	2,662	4,025	2,389	844
Euphausiids	332	1,092	1,152	760
Siphonophores (none colonial)	1,410	1,092	654	3,646
Salps	--	789	--	--
Larvaceans	--	445	--	1,452
Heteropods	--	263	441	--
Foraminifera	438	--	--	--
Ostracods	294	--	--	371
Doliolids	--	--	284	--

found only on one side or the other. A macroscopic inspection of the remainders of the samples confirmed this exclusiveness.

The ship's track at front 4 was planned to reveal both the general orientation of the front and its rate of advance (fig. 36). The track duplicated itself to some extent; the first part was from 0330 hours to 0707 hours, and the second was from 0828 hours to 1900 hours. The part 0707-0828 hours connects the two but is of no use in plotting the isotherms (fig. 36). Neither the general form nor the rate of advance was satisfactorily determined. On the first part, the front was in the form of a loop which may have become much changed, judging from the intersections of the 20° and 20.5° C. isotherm with the tract shortly after 0707 hours. (This assumes no serious error in the plotting of the track; e.g., through dead-reckoning navigation.) On the second part the front appears to have been oriented roughly north-east--south-west, but such an alignment also would arise if the front were oriented east-west and were moving north; in that event, the spurious alignment (NE-SW) would be due only to time lag between successive crossings of the northward-moving front. Both possibilities could co-exist, of course. If the front were moving north, its approximate speed would be given by the difference in latitude north of the 20° C. isotherm at about 0835 and 1715 hours; that is, about 4 miles in nearly 8 1/2 hours--approximately half a knot.

In view of the short time available, and the belief that this front would be comparable with front 2, no BT pass was made, unfortunately. As at front 2, hydrocasts were somewhat distant from the front, being about 20 km. apart. The restrictions on the discussion of the property profiles applied to front 2 also apply here.

The isotherms in the upper 100 m. deepen towards the warm side, as they did at front 2. There was a thermocline at 50-60 m. (cool side) to 70-90 m. (warm side).

The salinity profile (as at front 2) indicates a complicated salinity structure; this is shown by the T-S curves (fig. 37).

The T-S curve for the cool side is reasonably typical of California Current water in that area (marked salinity minimum), with some indication, by the low surface salinity relative to that of the general area, that the surface waters were upwelled. The T-S curve for the warm side shows a surface salinity consistent with that of California Current water in that area, but, like the T-S curve of the cool side at front 2, it also shows an anomaly: a marked salinity minimum was not present. One possible cause is that the warm water of this front was a mixture of California Current water and saltier, warmer water in the region (i.e., Gulf or equatorial Pacific water). If mixing were the cause, however, one might expect not only a small vertical salinity gradient (as is seen: S~34.50‰ in the upper 110 m.), but also a small vertical temperature gradient; such is found in the upper 50 m. but not from 50 to 100 m. depth.

These two T-S curves illustrate the changes that occurred during the 13 days between studies at front 2 and front 4. This was in spite of the superficial similarity. Surface temperatures were: front 2 - 19.96° to 21.74° C.; front 4 - 19.34° to 21.00° C.,--respective differences of 1.78° and 1.66° C. The surface salinities were: front 2 - 34.36 to 34.79 ‰; front 4 - 34.31 to 34.52 ‰. The decrease from 34.79 to 34.52‰ during the 13 day interval suggests that low salinity, probably upwelled (note lowered temperature, from 21.74° to

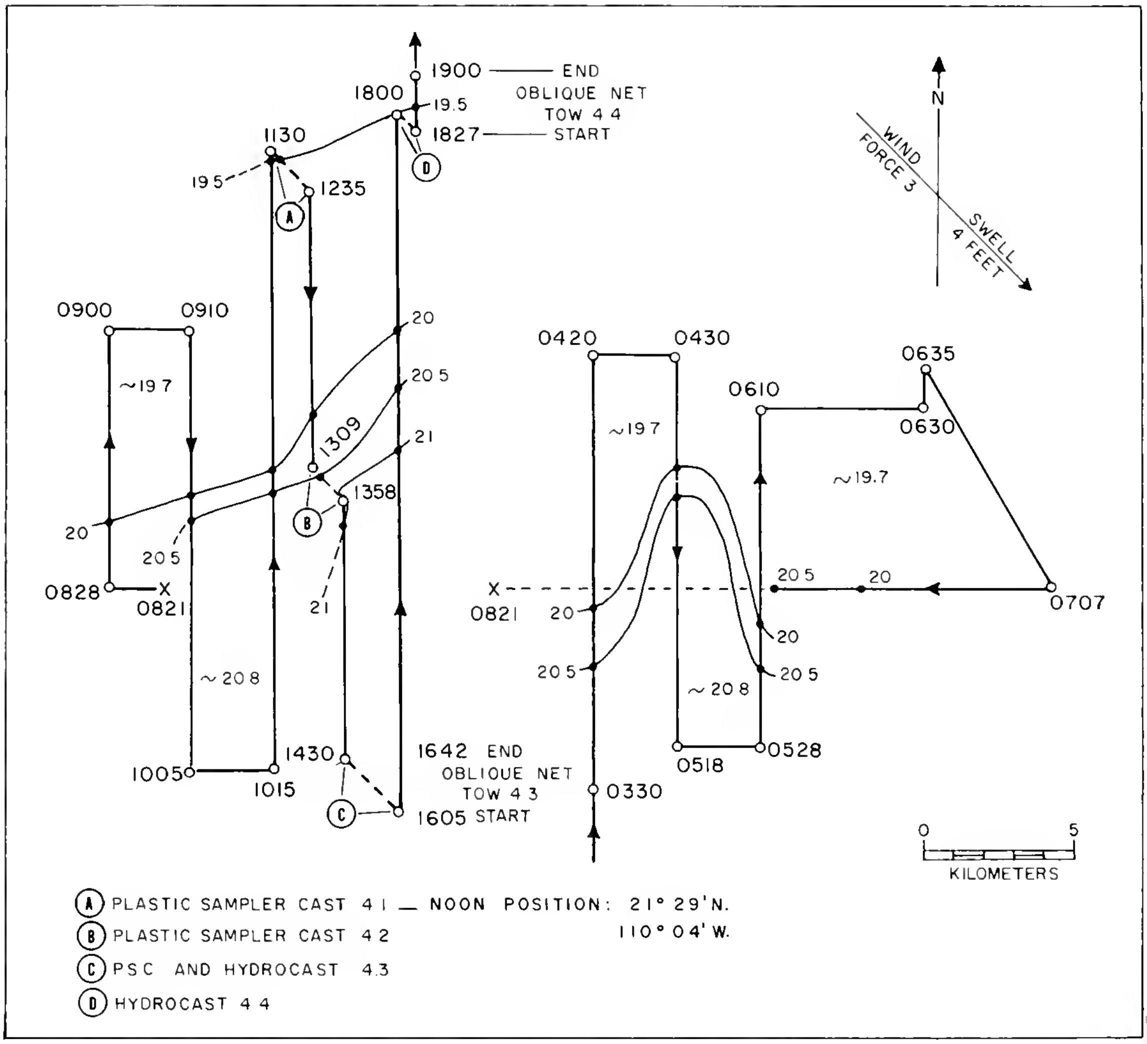

Figure 36.--Track at front 4 (23 May 1960), showing positions of hydrocasts, plastic sampler casts, and net tows. The track has been broken and separated at 0821 hours. (X) for clarity of presentation.

21.00° C.) water had mixed with the warm saline water on the warm side of this front. I assume that this upwelled cool, low-salinity water was on the cool side and gradually mixed with the water on the warm side, but at the same time the water on the cool side was being cooled further (19.96° down to 19.34° C.) by advection of upwelled water north of it.

Thermosteric anomaly, dissolved oxygen, and phosphate content show strong vertical gradients at depths corresponding roughly to the thermocline; the profiles of these properties qualitatively resemble that of the temperature.

Like front 2, but in contrast to front 5, there are strong density differences at any given depth down to about 150 m. at front 4. This front, much more than the rest, shows the density discontinuity commonly considered necessary to the existence of a front.

A plastic sampler cast was made on either side and in the middle of this front, though only three bottles per cast were used, at surface and depths of 25 and 40 m. (table 6).

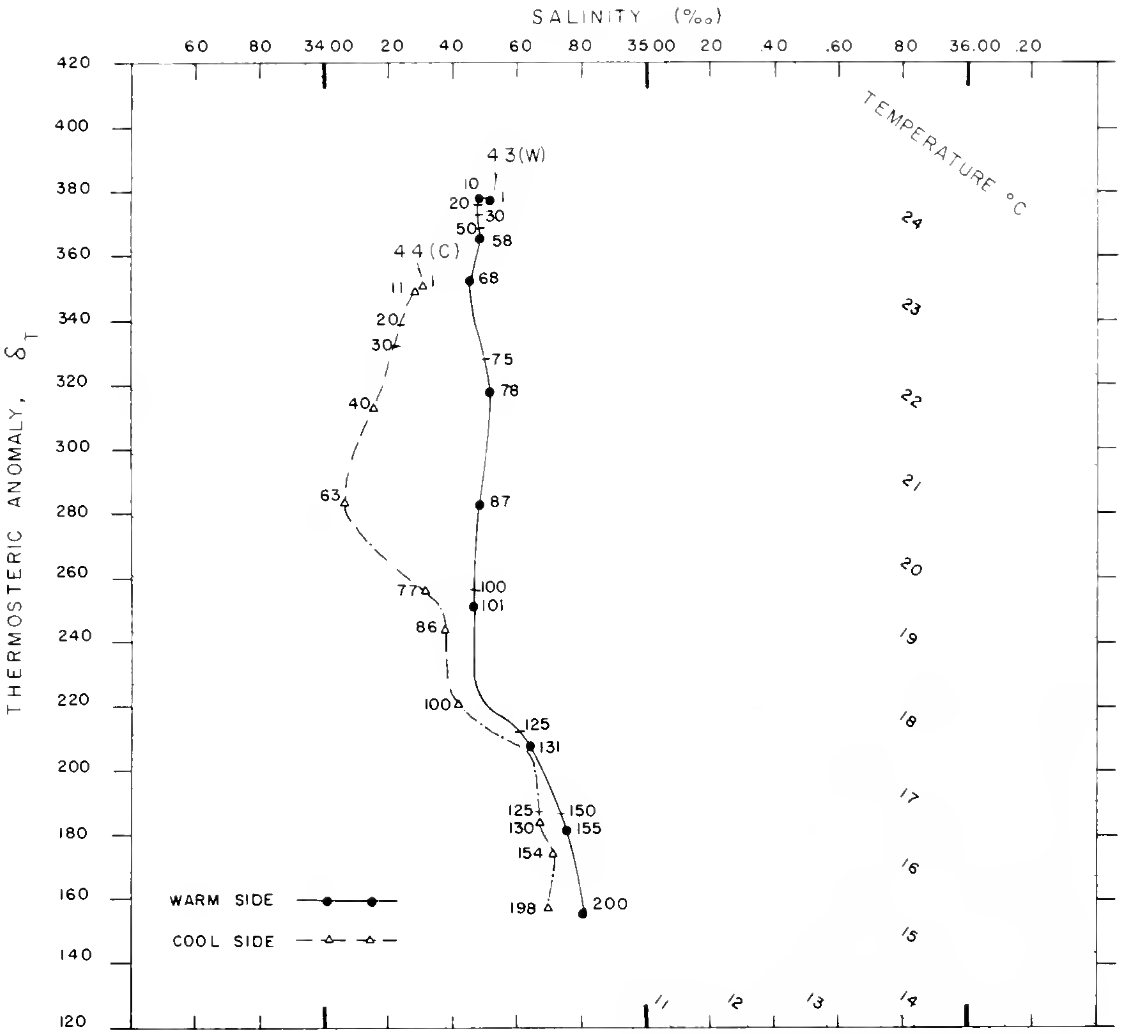

Figure 37.--T-S curves (on a δ_T field) for the two hydrocasts (4.3 on the warm (w) side, 4.4 on the cool (c) side) at front 4. Numbers against curves indicate depths.

Table 6.--Measurements of chlorophyll a made at three depths in the middle and on either side of front 4; units in mg./m.[3]

[w = warm side; m = middle; c = cool side]

Depth	Station		
	4.3 (w)	4.2 (m)	4.1 (c)
Meters			
0..................	0.031	0.090	0.559
25..................	.053	.239	.527
40..................	.019	.084	.969

SUMMARY

The most marked oceanographic feature of the entrance to the Gulf of California is a frontal system that extends from Cape San Lucas into the Pacific Ocean. This system is formed by three kinds of water: (1) Gulf of California water, warm and high in salinity; (2) California Current system water, cool and low in salinity; (3) equatorial Pacific water, warm and intermediate in salinity. The best studied part of the system, and most stable, is the area off Cape San Lucas.

The frontal system, at any rate the system off the Cape, is strongest in the spring when the California Current water in it consists largely of cold, upwelled water; the system persists throughout the summer and is weakest in the fall and winter.

The sharp front near Cape San Lucas is formed by warm, high-salinity Gulf water and cool, low-salinity California Current water. Out to sea, the equatorial Pacific water (warm, intermediate salinity) and California Current water form a generally weaker continuation. As a result of mixing and advection of cool, upwelled water from the north, parts of the system are formed of waters not readily assignable to particular types.

The interface between the waters forming the system is complicated; near Cape San Lucas it is Z-shaped in the vertical plane, the Gulf water penetrating the California Current water at depths around 30-50 m.

It is generally believed that plankton is aggregated by a convergent front, but our data, though supporting this view, are not conclusive.

Chlorophyll a values at the three depths are given in table 6. According to these values the highest concentration of chlorophyll was on the cool side at 40 m. The values for the warm side and the middle are quite similar and both are much lower then those from the cool side, which suggests that the sample in the middle may have been much more on the warm side than we supposed. The cool side was much richer in chlorophyll a, and therefore in phytoplankton.

The standardized volume of the zooplankton catch on the cool side was somewhat less than that on the warm side. This does not reflect the gross distribution of chlorophyll a, nor do the distributions of predominant organisms. The composition of the plankton evidently changed in the 13-day interval. A summary of the catches of oblique hauls at front 4 is given in table 5.

The information in table 5 shows that the composition of the plankton changed within the fortnight. Copepods became much more abundant on the cool side, and so did the siphonophores. Chaetognaths and euphausiids became less abundant on the cool side. Larvaceans persisted exclusively on the cool side. Heteropods, which were exclusively on the cool side at front 2, became exclusive to the warm side; ostracods were quite the reverse of the heteropods. Salps, formerly on the cool side only, were absent altogether from front 4 (judging from the aliquot).

We made no attempt to distinguish species, though this may actually elucidate the changes better; the data are sufficient to show that the biota at front 4 differed significantly from that at front 2. I presume that this is consequent upon the oceanographic changes that occurred.

RECOMMENDATIONS

With regard to future work, firstly, much more needs to be learned about the area in general and the seasonal variability of the Cape San Lucas frontal system; secondly, new applications of known methods (e.g., multiple-ship operations and dye-markers to study convergence, divergence, and other frontal movements) should be tried; thirdly, the shortcomings of commonly used methods, as well as the variations used in the present study, indicate the need for new and improved gear, such as the thermistor chain (La Fond, 1961b), infrared radiometers, in situ salinity, density, and oxygen recorders which are becoming available. Attention also should be given to the distribution, in the neighborhood of the system, of organisms likely to be indicators of the different types of water forming the system.

ACKNOWLEDGEMENTS

The following oceanographers provided generous help and many useful suggestions, in particular, Joseph L. Reid, Jr. of the Scripps Institution of Oceanography; J.F.T. Saur of the Bureau of Commercial Fisheries at Stanford University; Klaus Wyrtki of the Scripps Institution and its Tuna Research Program; and E. O. Sette, Robert S. Arthur, and Milner B.

Schaefer who read all or parts of the manuscript and made many helpful comments.

My supervisor, Maurice Blackburn, gave constant encouragement and guidance.

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